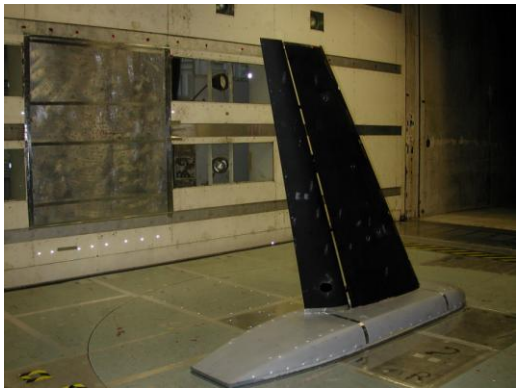

Summary of the First AIAA CFD High Lift Prediction Workshop (invited)

C. L. Rumsey
Senior Research Scientist, NASA Langley Research Center, Hampton, VA
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Applications Engineer, University of Wyoming, Laramie, WY
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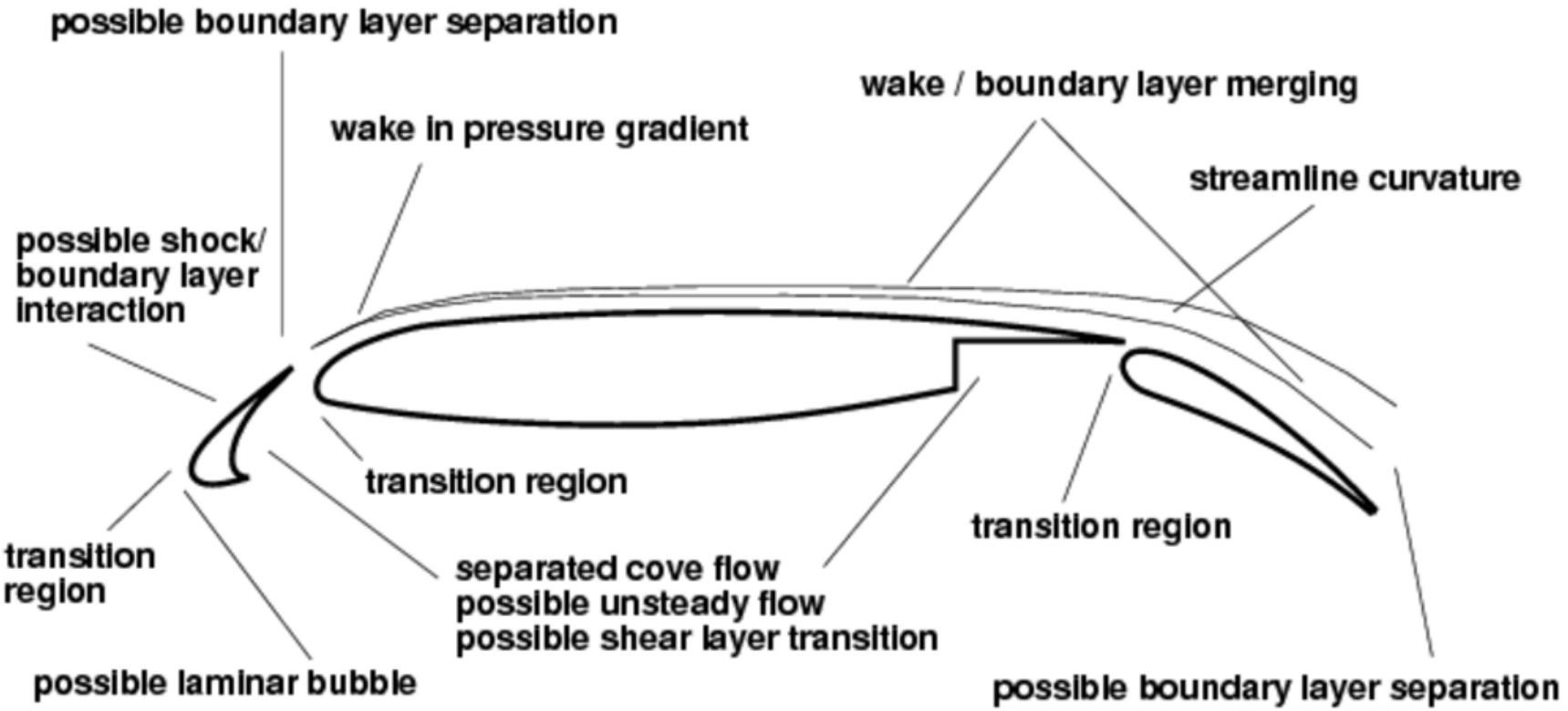
49th AIAA Aerospace Sciences Meeting, January 2011, Orlando ,FL

Outline

- Introduction
- Summary of entries
- Lift curve and polar comparisons
- Grid convergence behavior
- Predicting deltas between Config 1 and 8
- Surface pressure and skin friction
- Effect of support brackets
- Statistical analysis
- Conclusions & recommendations

Introduction

- Prediction of high-lift flows is challenging



Introduction

- Open international High Lift Prediction Workshops (HiLiftPW)
  - Bring experts together
  - Advance state-of-the-art
  - NASA Trapezoidal Wing the subject of HiLiftPW-1
- Long-term objectives of workshop series
  - Assess current prediction capability
  - Develop modeling guidelines
  - Advance understanding of physics
  - Enhance CFD prediction capability for design and optimization
  - Provide impartial forum
  - Identify areas needing additional research & development

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  - **Assess current prediction capability**
  - Develop modeling guidelines
  - Advance understanding of physics
  - Enhance CFD prediction capability for design and optimization
  - **Provide impartial forum**
  - **Identify areas needing additional research & development**
- **Looking for: overall collective results, trends, and outliers**

Summary of workshop entries

- 21 groups submitted 39 entries
  - 25 entries “complete”, 10 entries incomplete, 4 entries very limited (special studies)
  - 15 different CFD codes
- 11 entries were changed after the workshop
  - 2 replacements
  - 3 brand new
  - 6 minor updates, changes, or additions
- Grids
  - Nine committee-supplied grids employed
  - Seven participant grids employed
  - Medium grid sizes varied: most had 20-50 million unknowns
  - More details in earlier introductory paper (Slotnick et al)

“Complete” = 3 or more grid sizes used for alpha=13 and 28, and at least 5 alphas used for both polars

Summary of entries

	001	002	003.01	003.02	003.03	004	005.01	005.02	006	007	008.01	008.02	008.03	009	010	011	012.01	012.02	013.01	013.02	013.03	014.01	014.02	014.03	014.04	014.05	015	016	017.01	017.02	017.03	017.04	017.05	018	019	020.01	020.02	021.01	021.02
Code	CFX	CFD++	OVER	OVER	OVER	HIFUN	FUN3D	NSU3D	FUN3D	TAU	TAU	TAU	TAU	POWER	EDGE	NSU3D	TAS	UPACS	CFD++	CFD++	CFD++	OVER	OVER	OVER	OVER	OVER	USM3D	FUN3D	FUN3D	CFL3D	CFL3D	CFL3D	CFL3D	CFL3D	ELSA	NSMB	USM3D	USM3D	NSU3D	NSU3D
Type	N	C	N	N	N	C	N	N	N	N	N	N	N	B	N	N	N	C	C	C	C	N	N	N	N	N	C	N	N	C	C	C	C	C	C	C	C	N	N
Grid	UX9	UH13	SX3	SX3	SX3	UH14	UH6	UH6	UT5	UH8	UH7	UH7	UH7	CB16	UH8	UT12	UH15	SX11	UT5	UT5	UX9	SX3	SX3	SX3	SX3	SX3	UT4	UT5	UH6	SX1	SX1	SX2	SX1	SX1	SX10	UT4	UT4	UH6	UH6
Turb	SST*	KE*	SA*	SA*	SA*	SA	SA	SA	SA	SA	SA	SST	RSM	VLES	SA	SA	SA*	SA*	SA	KE*	KE*	SA*	SA*	SA*	SST	SA	SA	SA	SA	SST	SA	SST	SA	SA	SST	KO	KO*	SA	SST
Notes	Trans-ition, limited config 8		Bracket	brckets off on bracket-like grid	Config 8 grid study			Thin, no F	No polars	Bracket	No config 8, no F	No config 8, no F	No config 8, no F	Trans-ition, polars on F, Bracket	Thin, Bracket	Thin	Bracket		Used node-center grids	Used node-center grids		Bracket	HLLC, limited config 8	Central, no grid study, no config 8	No config 8, Bracket	Only 1 condition run				Thin	Thin	Thin				No F		Thin	Thin, no grid study

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Type	N	C	N	N	N	C	N	N	N	N	N	N	N	N	B	N	N	N	C	C	C	C	N	N	N	N	N	C	C	N	N
Grid	UX9	UH13	SX3	SX3	SX3	UH14	UH6	UH6	UT5	UH8	UH7	UH7	UH7	UH7	CB16	UH8	UT12	UH15	SX11	UT5	UT5	UX9	SX3	SX3	SX3	SX3	SX3	UT4	UT4	UH6	UH6
Turb	SST*	KE*	SA*	SA*	SA*	SA	SA	SA	SA	SA	SA	SST	RSM	VLES	SA	SA	SA	SA*	SA*	SA	KE*	KE*	SA*	SA*	SA*	SST	SA	KO	KO*	SA	SST
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008.01

Person or group number

Submission number if more than 1 from group

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Type	N	C	N	N	N	C	N	N	N	N	N	N	N	B	N	N	N	C	C	C	C	N	N	N	N	N	C	N	N	C	C	C	C	C	C	C	C	N	N
Grid	UX9	UH13	SX3	SX3	SX3	UH14	UH6	UH6	UT5	UH8	UH7	UH7	UH7	CB16	UH8	UT12	UH15	SX11	UT5	UT5	UX9	SX3	SX3	SX3	SX3	SX3	UT4	UT5	UH6	SX1	SX1	SX2	SX1	SX1	SX10	UT4	UT4	UH6	UH6
Turb	SST*	KE*	SA*	SA*	SA*	SA	SA	SA	SA	SA	SA	SST	RSM	VLES	SA	SA	SA*	SA*	SA	KE*	KE*	SA*	SA*	SA*	SST	SA	SA	SA	SA	SST	SA	SST	SA	SA	SST	KO	KO*	SA	SST
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Type	N	C	N	N	N	C	N	N	N	N	N	N	N	B	N	N	N	C	C	C	C	N	N	N	N	N	C	N	N	C	C	C	C	C	C	C	C	N	N
Grid	UX9	UH13	SX3	SX3	SX3	UH14	UH6	UH6	UT5	UH8	UH7	UH7	UH7	CB16	UH8	UT12	UH15	SX11	UT5	UT5	UX9	SX3	SX3	SX3	SX3	SX3	UT4	UT5	UH6	SX1	SX1	SX2	SX1	SX1	SX10	UT4	UT4	UH6	UH6
Turb	SST*	KE*	SA*	SA*	SA*	SA	SA	SA	SA	SA	SA	SST	RSM	VLES	SA	SA	SA*	SA*	SA	KE*	KE*	SA*	SA*	SA*	SST	SA	SA	SA	SA	SST	SA	SST	SA	SA	SST	KO	KO*	SA	SST
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Turb	SST*	KE*	SA*	SA*	SA*	SA	SA	SA	SA	SA	SA	SS	RSM	VLES	SA	SA	SA*	SA*	SA	KE*	KE*	SA*	SA*	SA*	SST	SA	SA	SA	SA	SST	SA	SST	SA	SA	SST	KO	KO*	SA	SST
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Turb	SST*	KE*	SA*	SA*	SA*	SA	SA	SA	SA	SA	SA	SST	RSM	VLES	SA	SA	SA*	SA*	SA	KE*	KE*	SA*	SA*	SA*	SST	SA	SA	SA	SA	SST	SA	SST	SA	SA	SST	KO	KO*	SA	SST
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Turb	SST*	KE*	SA*	SA*	SA*	SA	SA	SA	SA	SA	SA	SST	RSM	VLES	SA	SA	SA*	SA*	SA	KE*	KE*	SA*	SA*	SA*	SST	SA	SA	SA	SA	SST	SA	SST	SA	SA	SST	KO	KO*	SA	SST
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Type	N	C	N	N	N	C	N	N	N	N	N	N	N	B	N	N	N			C	C	N	N	N		N				C	C	C	C	N	N
Grid	UX9	UH13	SX3	SX3	SX3	UH14	UH6	UH6	UT5	UH8	UH7	UH7	UH	CB	8	12	UH15	SX11	UT5	UT5	UX9	SX	3	X3	SX3	SX3	U	4	5	6	SX1	SX10	UT4	UT4	UH6	UH6
Turb	SST*	KE*	SA*	SA*	SA*	SA	SA	S	A	A	A	SST	RSM	VLES	SA	SA	SA	S	E*	KE*	SA*	SA*	SA*	S	A	SA	SA	SA	SST	A	SST	A	SA	KO	KO*	SA	SST
Notes	Trans-ition, limited config 8		Bracket	brckets off on bracket-like grid	Config 8 grid study			Thin, no F	No polars	Bracket	No config 8, no F	No config 8, no F	No config 8, no F	Trans-ition, polars on F, Bracket	Thin, Bracket	Thin	Bracket		Used node-center grids	Used node-center grids		Bracket	HLLC, limited config 8	Central, no grid study, no config 8	No config 8, bracket	Only 1 conditio n run						Thin	Thin	Thin			No F		Thin	Thin, no grid study

Additional runs with support brackets included

N=node-centered
C=cell-centered
B=Boltzmann

SX=Structured
UX=Unstructured hex
UT=Unstructured tet
UH=Unstructured hybrid
CB=Cartesian based

1=Str point-matched A
2=Str point-matched B
3=Str overset A
4=Unstr tet cell-center A
5=Unstr tet node-center A
6=Unstr hybrid (merged from 5)
7=Unstr hybrid node-center A
8=Unstr hybrid node-center B
9=Unst hex (from 1)

SA=Spalart-Allmaras
SST=Menter Shear Stress Transport
KE=K-Epsilon
RSM=Reynolds Stress Model
KO=Wilcox K-Omega
VLES=Very Large Eddy Simulation
* = modified in some way

Summary of entries

	001	002	003.01	003.02	003.03	004	005.01	005.02	006	007	008.01	008.02	008.03	009	010	011	012.01	012.02	013.01	013.02	013.03	014.01	014.02	0	0	0	0	0	0	017.02	017.03	017.04	017.05	018	019	020.01	020.02	021.01	021.02
Code	CFX	CFD++	OVER	OVER	OVER	HIFUN	FUN3D	NSU3D	FUN3D	TAU	TAU	TAU	TAU	POWER	EDGE	NSU3D	TAS	UPACS	CFD++	CFD++	CFD++	OVER	OVER							CFL3D	CFL3D	CFL3D	CFL3D	ELSA	NSMB	USM3D	USM3D	NSU3D	NSU3D
Type	N	C	N	N	N	C	N	N	N	N	N	N	N	B	N	N			C	C	C	N	N							C	C	C	C	C	C	C	C	N	N
Grid	UX9	UH13	SX3	SX3	SX3	UH14	UH6	UH6	UT5	UH8	UH7	UH	UH	16	H8	UT12	UH15	SX11	UT5	UT5	UX	3	SX3	3	3	3	4	5	6	X1	SX1	SX2	SX1	SX1	SX10	UT4	UT4	UH6	UH6
Turb	SST*	KE*	SA*	SA	SA	S	S	A	A	SA	SA	SST	RSM	VLES	SA	SA	SA	S*	A	KE*	KE*	SA*	SA*	SA*	SST	SA	SA	SA	SA	SST	SA	SST	SA	SA	SST	KO	KO*	SA	SST
Notes	Trans-ition, limited config 8		Bracket	brckets off on bracket-like grid	Config 8 grid study			Thin, no F	No polars	Bracket	No config 8, no F	No config 8, no F	No config 8, no F	Trans-ition, polars on F, Bracket	Thin, Bracket	Thin	Bracket		Used node-center grids	Used node-center grids		Bracket	HLLC, limited config 8	Central, no grid study, no config 8	No config 8, Bracket	Only 1 , conditio n run				Thin	Thin	Thin			No F		Thin	Thin, no grid study

Transition modeled

N=node-centered
C=cell-centered
B=Boltzmann

SX=Structured
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UT=Unstructured tet
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1=Str point-matched A
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Summary of entries

	001	002	003.01	003.02	003.03	004	005.01	005.02	006	007	008.01	008.02	008.03	009	010	011	012.01	012.02	013.01	013.02	015	016	017.01	017.02	017.03	017.04	017.05	018	019	020.01	020.02	021.01	021.02
Code	CFX	CFD++	OVER	OVER	OVER	HIFUN	FUN3D	NSU3D	FUN3D	TAU	TAU	TAU	TAU	POWER	EDGE	NSU3D	TAS	UPACS	CFD++	CFD++	USM3D	FUN3D	FUN3D	CFL3D	CFL3D	CFL3D	CFL3D	ELSA	NSMB	USM3D	USM3D	NSU3D	NSU3D
Type	N	C	N	N	N	C	N	N	N	N	N	N	N	B	N	N	N	C	C	C	C	N	N	C	C	C	C	C	C	C	C	N	N
Grid	UX9	UH13	SX3	SX3	SX3	UH14	UH6	UH6	UT5	UH8	UH7	UH7	UH7	CB16	UH8	UT12	UH15	SX11	UT5	UT8	UX9	SX3	SX3	SX3	SX3	SX3	UT5	UT5	UH6	SX1	SX1	SX1	SX10	UT4	UT4	UH6	UH6
Turb	SST*	KE*	SA*	SA*	SA*	SA	SA	SA	SA	SA	SA	ST	SM	VLES	SA	SA	SA*	SST*	SA	KE*	KE*	SA*	SA*	SA*	SST	SA	SA	SA	SA	SST	SA	SA	SST	KO	KO	SA	SST
Notes	Trans-ition, limited config 8		Bracket	brckets off on bracket-like grid	Config 8 grid study			Thin, no F	No polars	Bracket	No config 8, no F	No config 8, no F	No config 8, no F	Trans-ition, polars on F, Bracket	Thin, Bracket	Thin	Bracket		Used node-center grids	Used node-center grids		Bracket	HLLC, limited config 8	Central, no grid study, no config 8	No config 8, Bracket	Only 1 condition run					Thin	Thin	Thin				No F			Thin	Thin, no grid study

Thin-layer type

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LIFT CURVE AND POLAR COMPARISONS

What to watch for

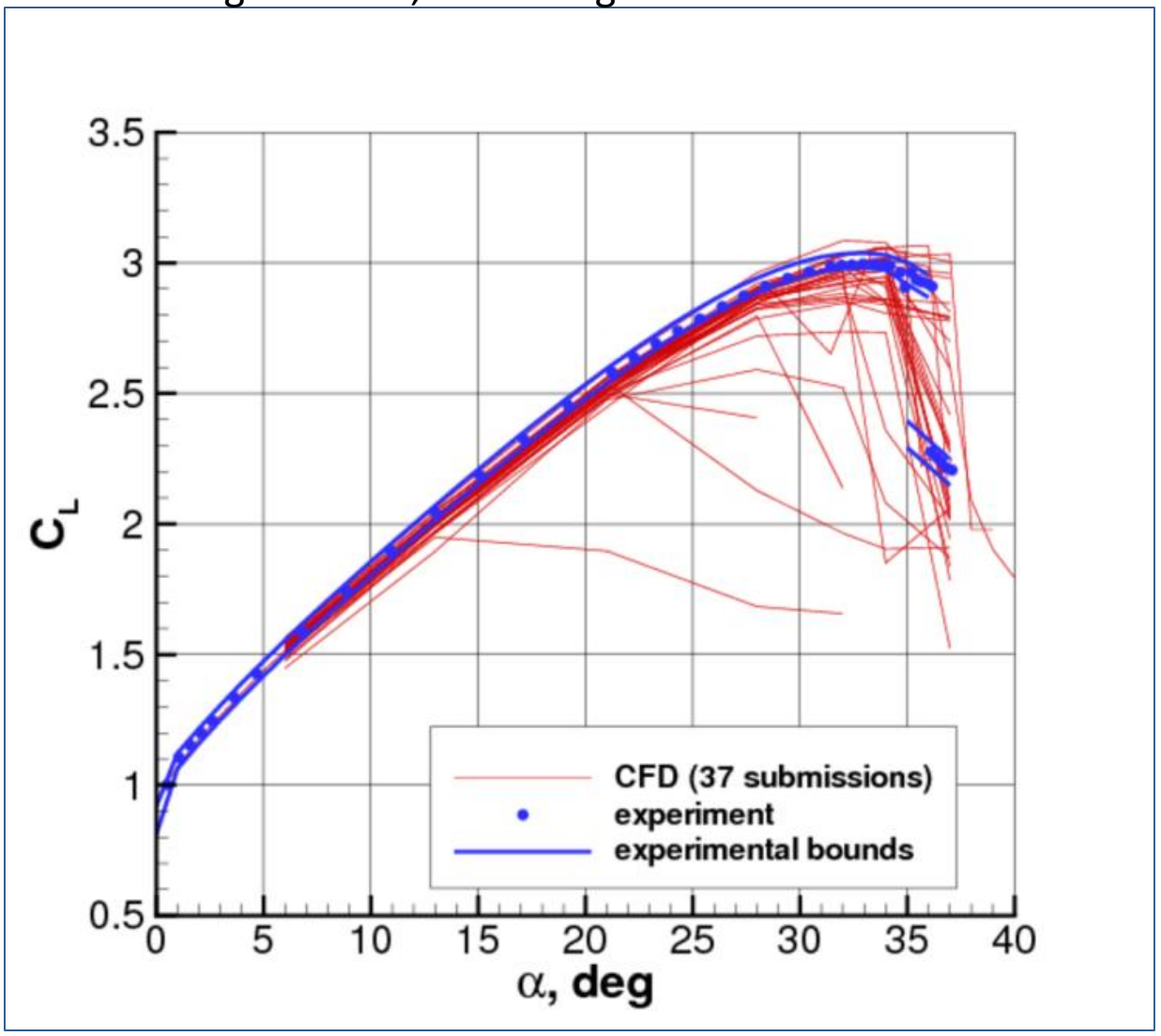
- As a group, CFD tended to under-predict lift, drag, and magnitude of moment compared to experiment
- Nonetheless, many participants predicted $C_{L,max}$ reasonably well
- More spread among CFD solutions at high angles of attack
- There were some clear outliers at high alphas
- SA model tended to yield higher $C_{L,max}$ than other models
  - Exception: 2 models that included transition

Summary of all results

-In the collective, CFD tended
to under-predict lift, drag,
and moment magnitude

-There were CFD outliers,
especially at higher alphas

Configuration 1, medium grid*



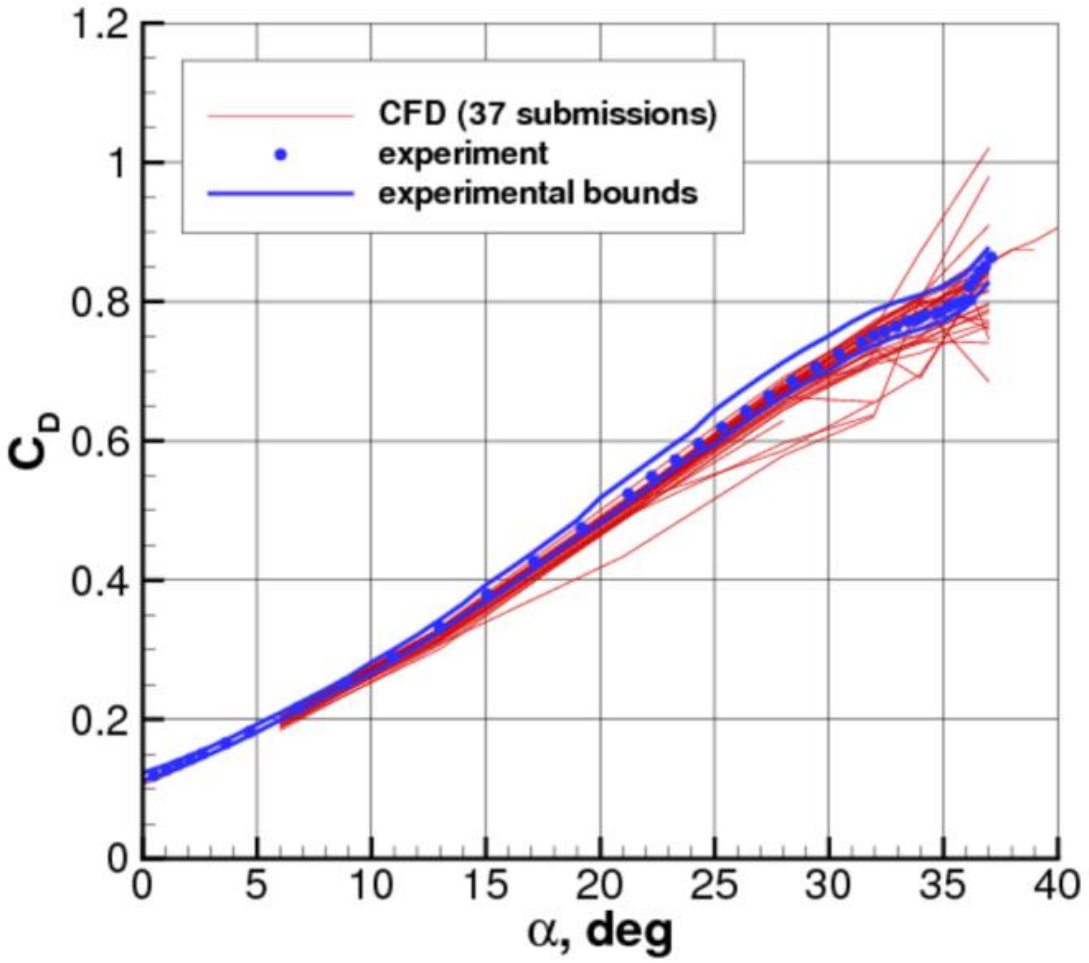
* except entry 009 on F

Summary of all results

Configuration 1, medium grid*

-In the collective, CFD tended
to under-predict lift, drag,
and moment magnitude

-There were CFD outliers,
especially at higher alphas



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Summary of all results

-In the collective, CFD tended
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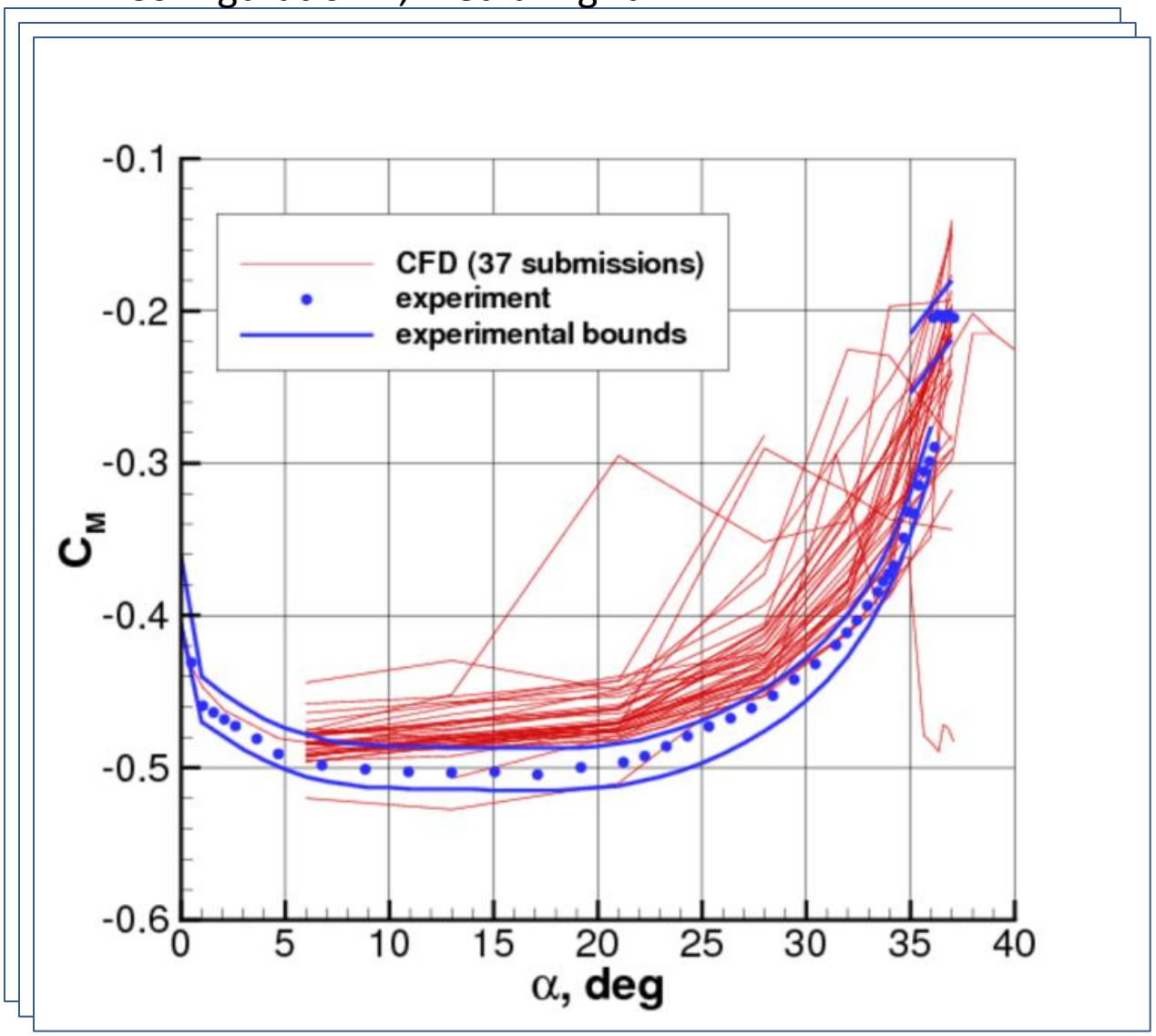
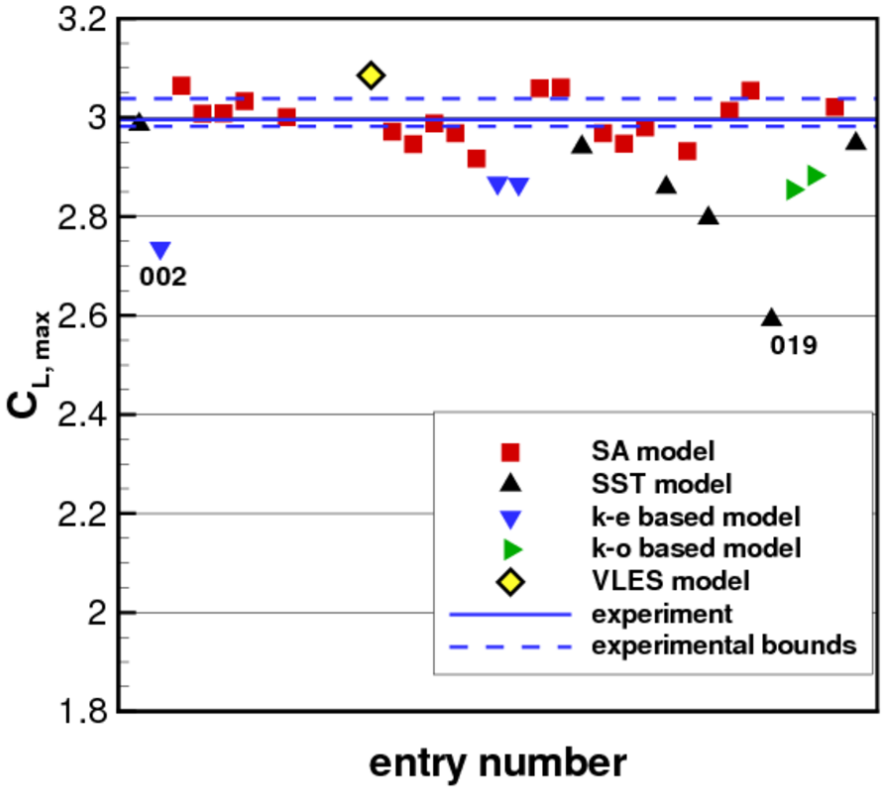
Configuration 1, medium grid*

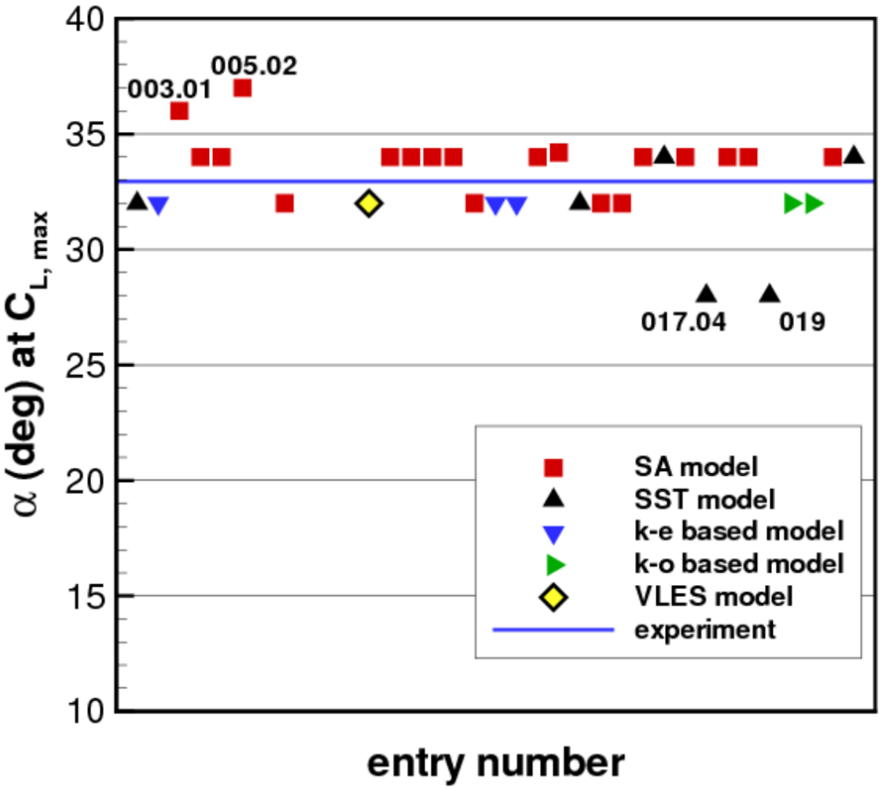


* except entry 009 on F

Predictions of maximum lift

Configuration 1, medium grid*





-Many entries predicted $C_{L,max}$ reasonably well

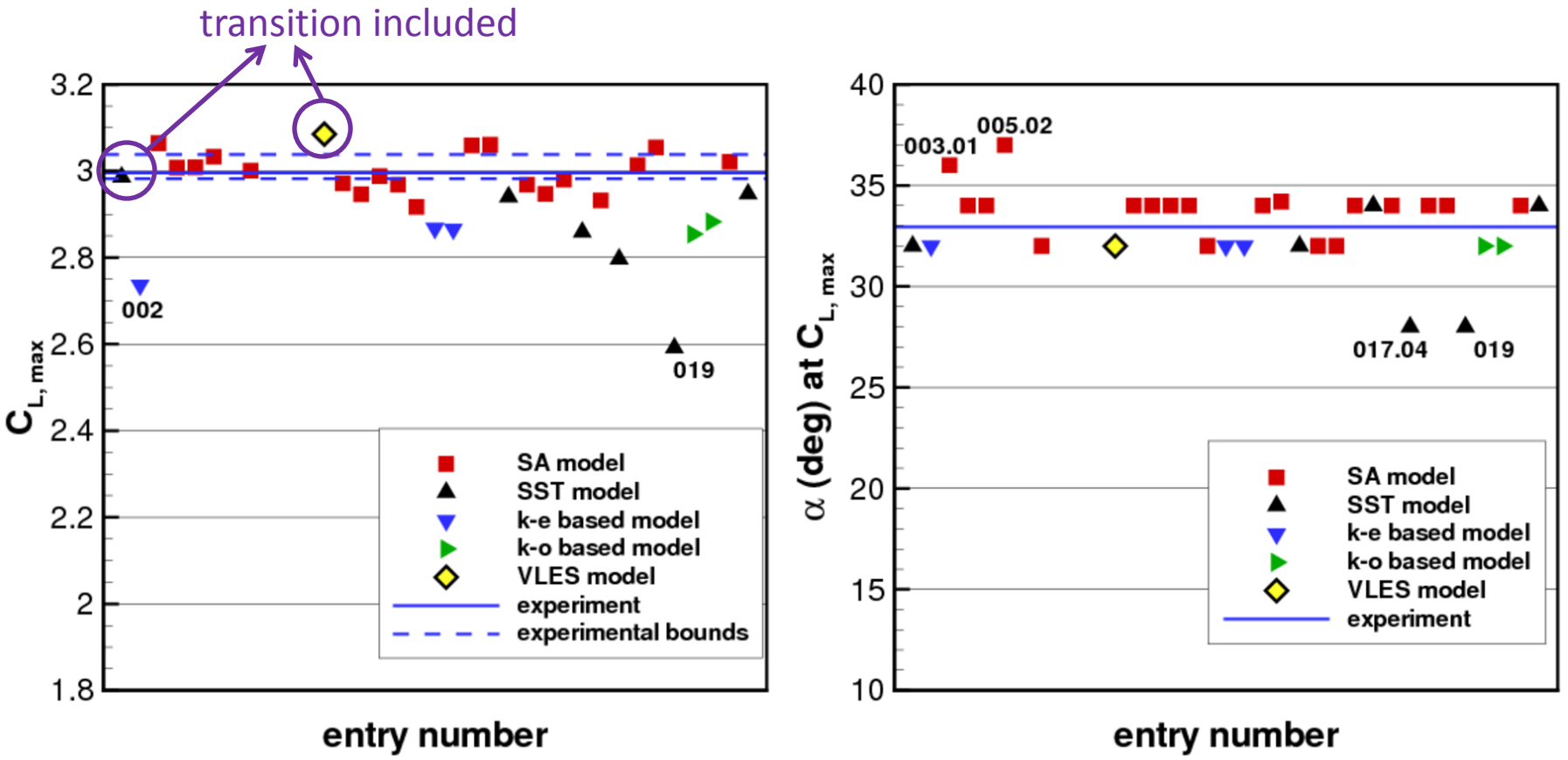
-Aberrant entries with possible issue of I.C. dependence not shown

-As a group, SA model predicted $C_{L,max}$ to be higher than other models

* except entry 009 on F

Predictions of maximum lift

Configuration 1, medium grid*



-Many entries predicted $C_{L,max}$ reasonably well

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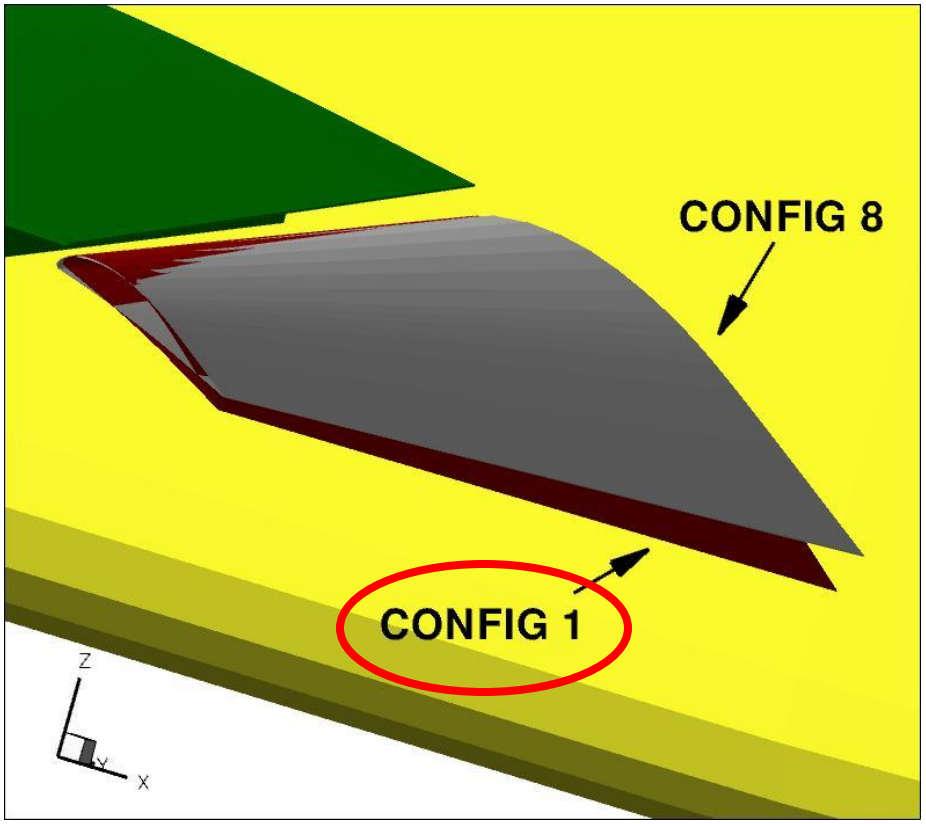
* except entry 009 on F



GRID CONVERGENCE BEHAVIOR

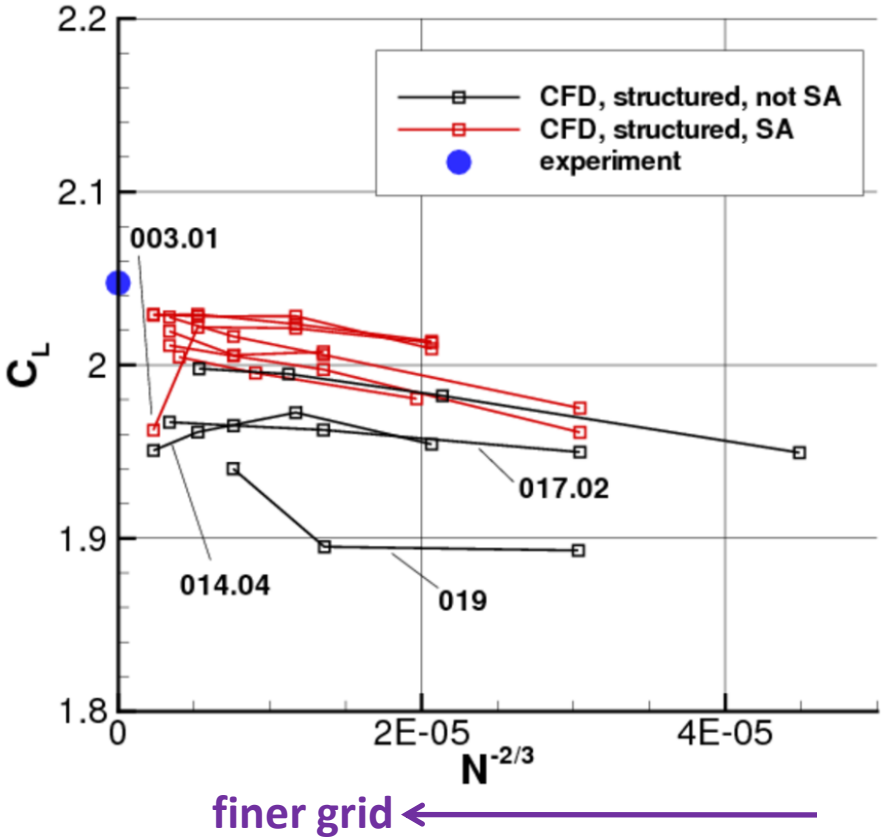
What to watch for

- Grid refinement trends were generally in the right direction (toward experiment as grid was refined)
- Some entries exhibited aberrant behavior
  - Possibly due to initial condition dependency reported by some participants

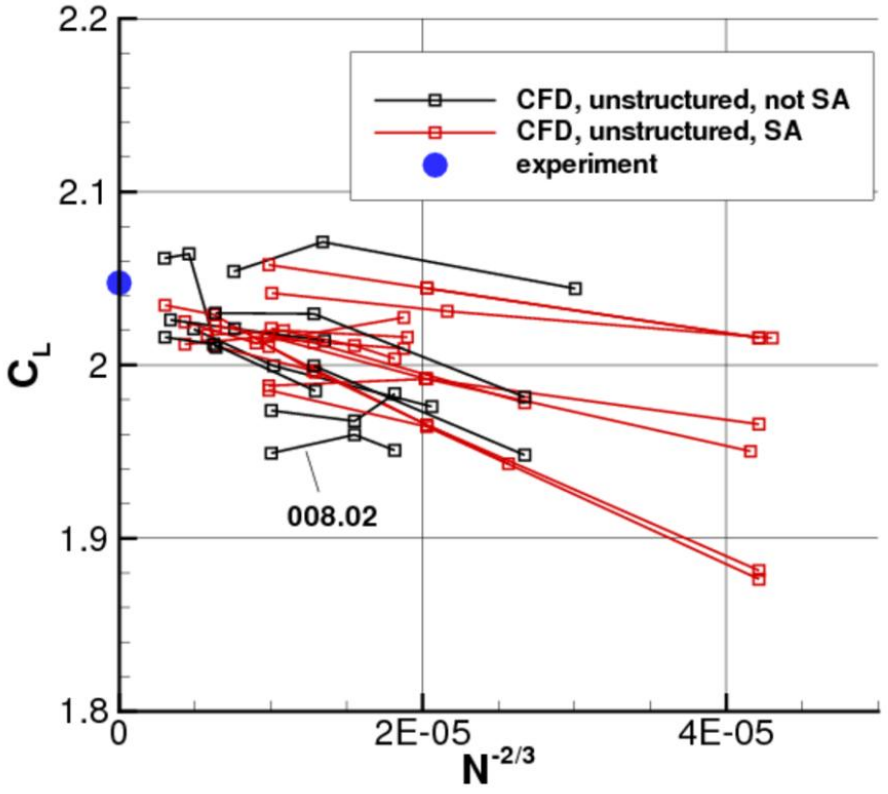
Grid convergence of C_L at alpha=13°

Configuration 1

Structured



Unstructured

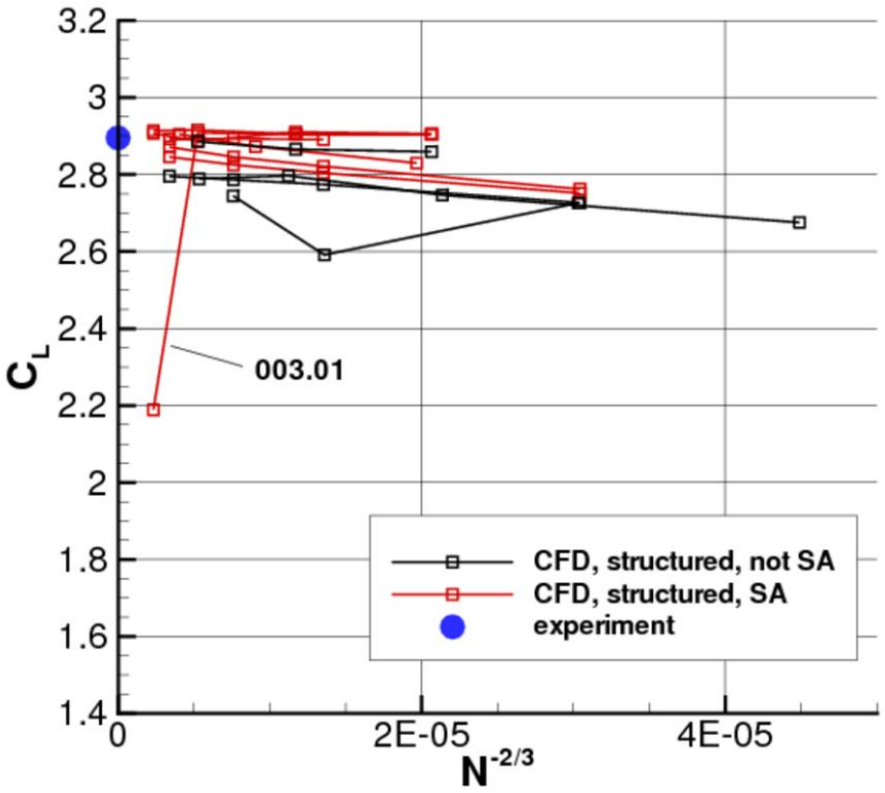


-For structured grids, non-SA models showed trend toward lower lift than SA
-In general, lift tended to increase as grid refined (approaching experiment)
-003.01 showed aberrant behavior on extra-fine (XF) grid only

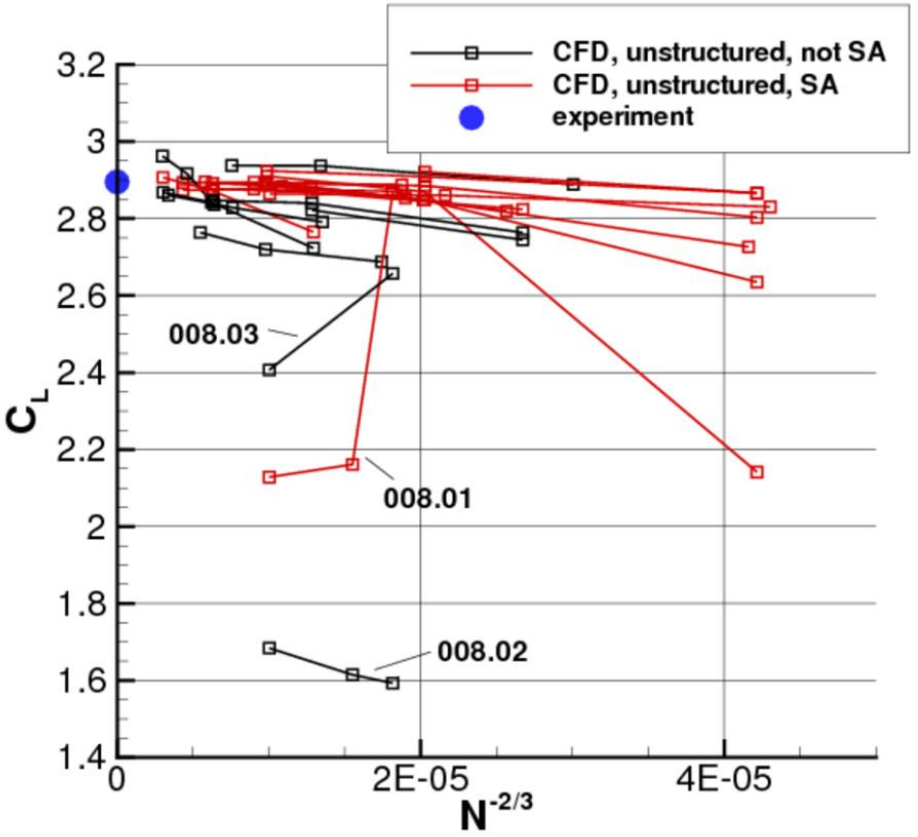
Grid convergence of C_L at alpha=28°

Configuration 1

Structured



Unstructured



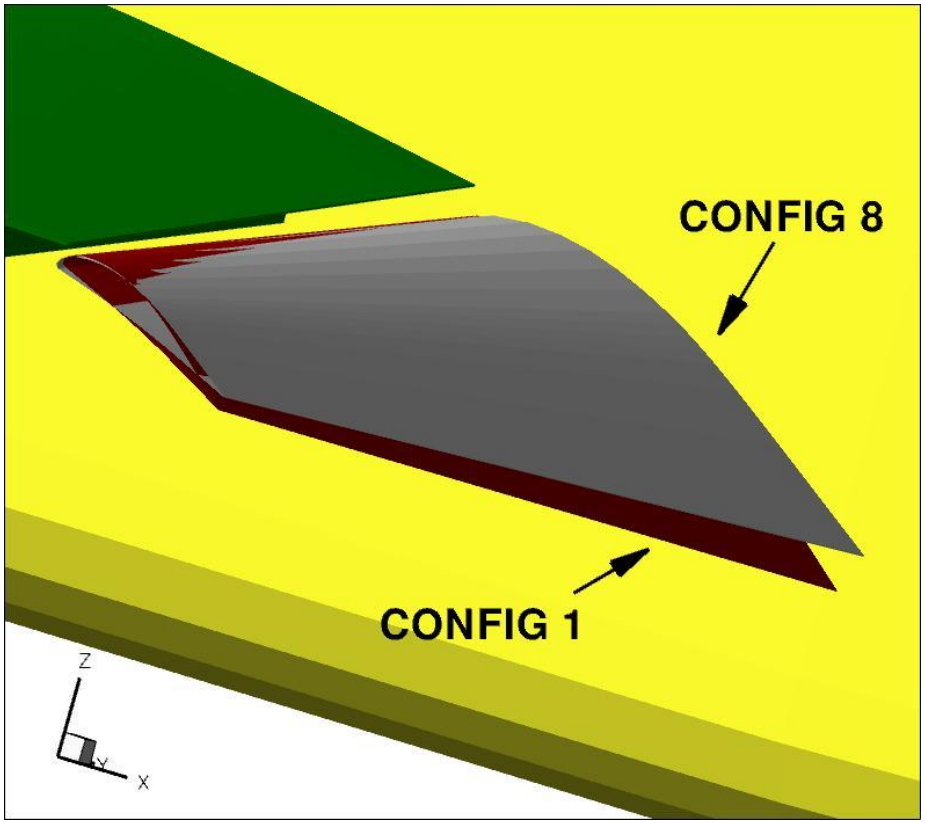
finer grid ←

-008.01, 008.02, 008.03 showed aberrant behavior

-003.01 showed aberrant behavior on XF grid only

Possible issue of initial condition dependency

-Identified need to restart from previously-converged solution at lower alpha



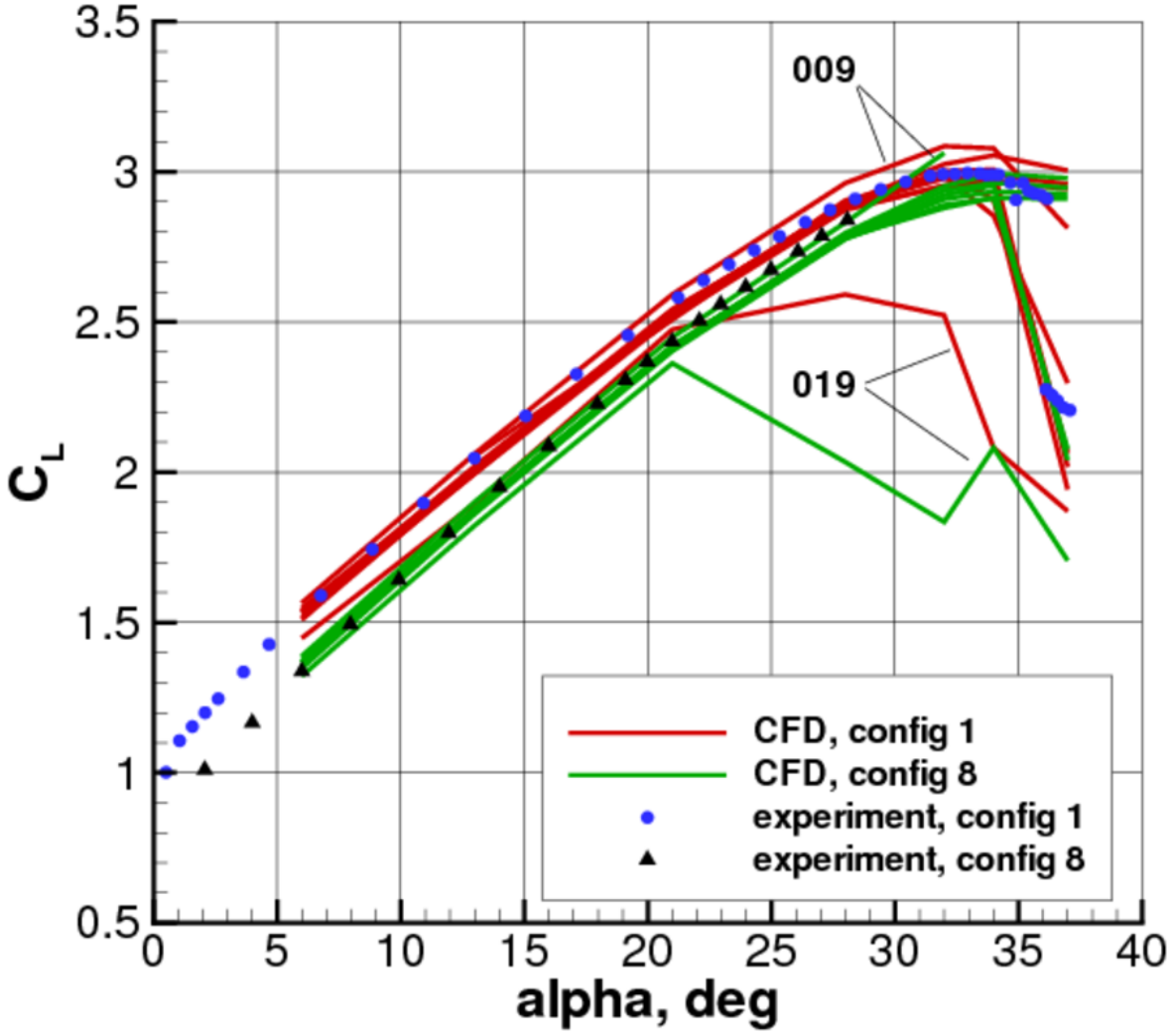
PREDICTING DELTA C_L BETWEEN CONFIGURATIONS

What to watch for

- Qualitative assessment of trends in lift coefficient (between configurations 1 and 8)
- SA tended to yield higher lift near stall than other models
- Two entries that accounted for transition stood out

Qualitative prediction of lift curve differences

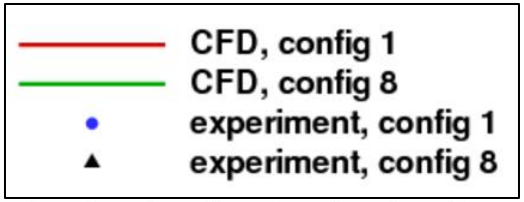
Nine different CFD codes, Medium grids*

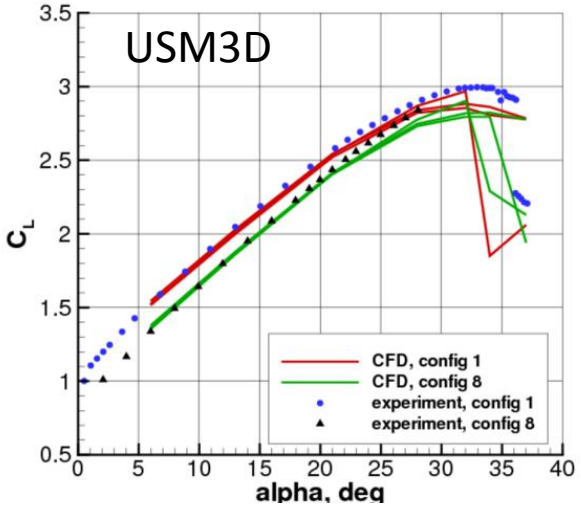


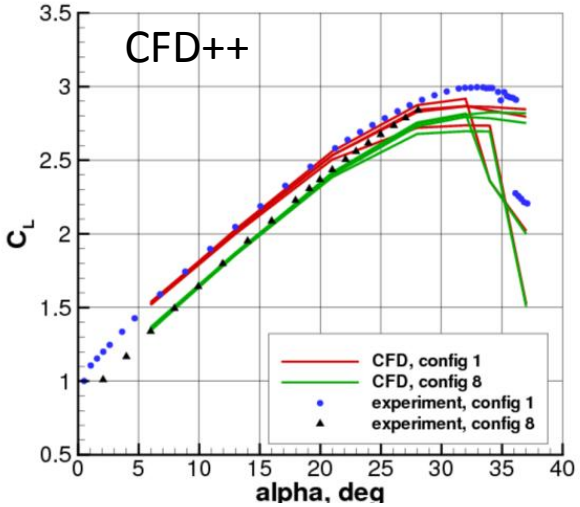
* except entry 009 on F

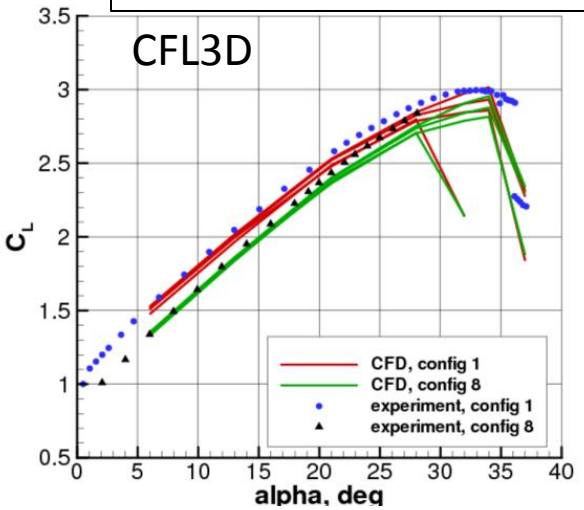
Qualitative prediction of lift curve differences

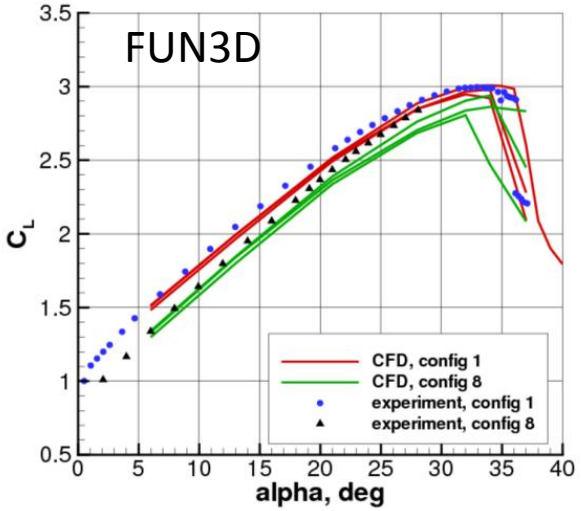
Six remaining CFD codes, Medium grids

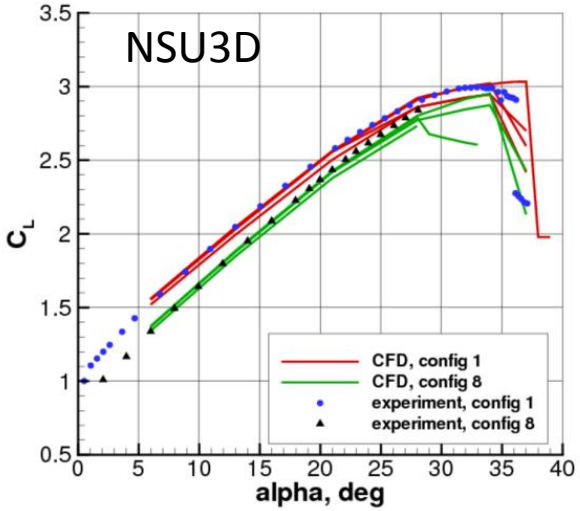


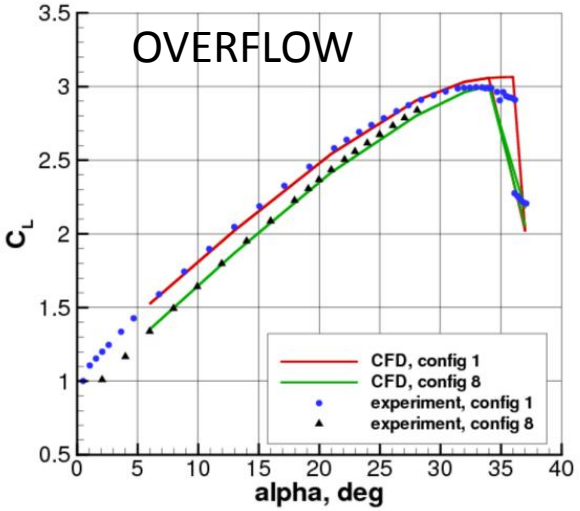








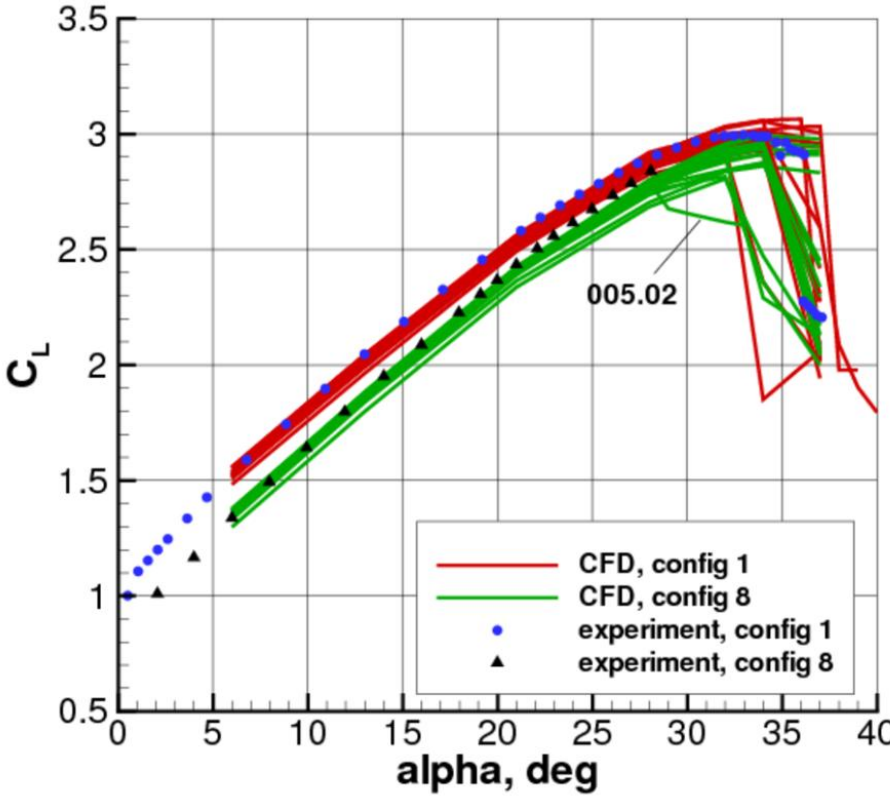




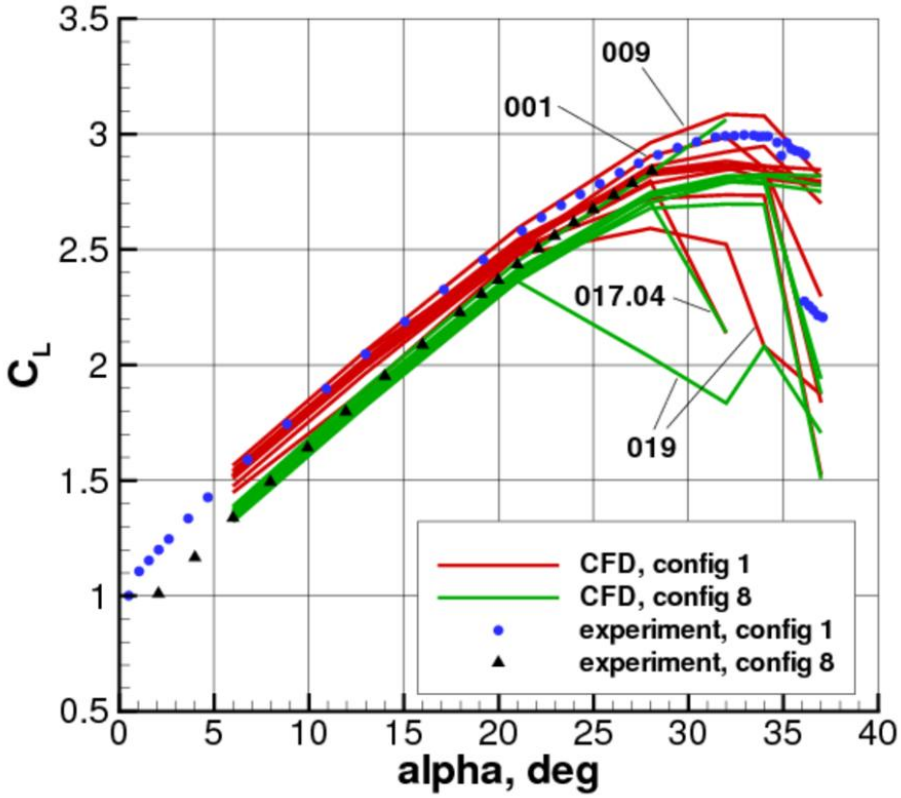
Qualitative prediction of lift curve differences

Medium grids*

SA model



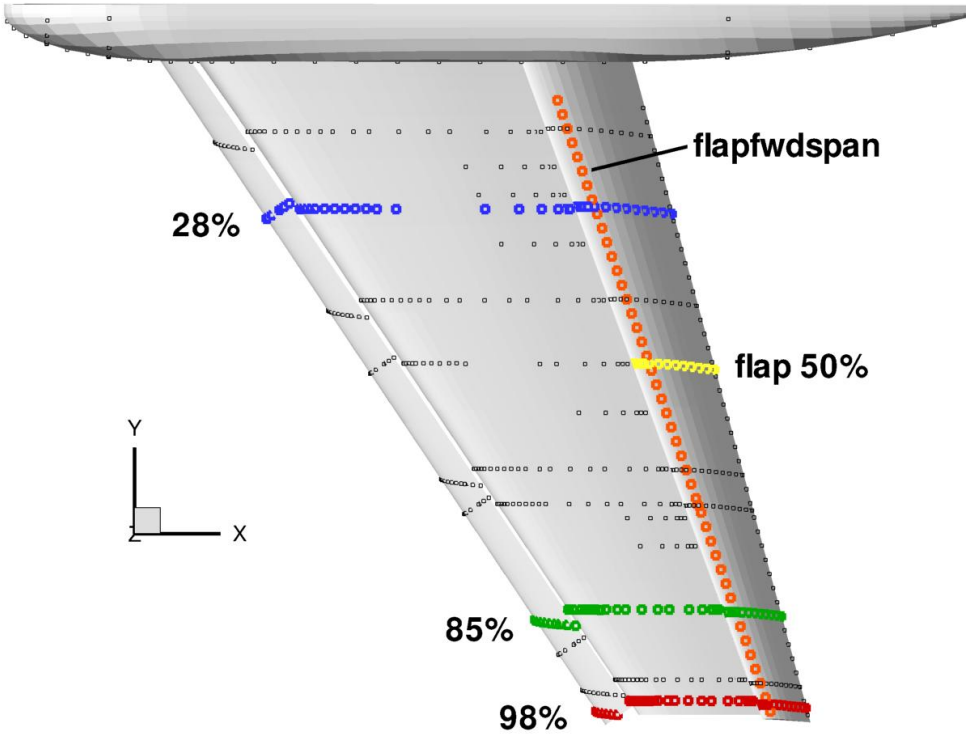
Other models



-SA generally yielded higher lift near stall than other models

-Two of the "others" that stand out with higher levels are 001 and 009 (both accounted for transition)

* except entry 009 on F

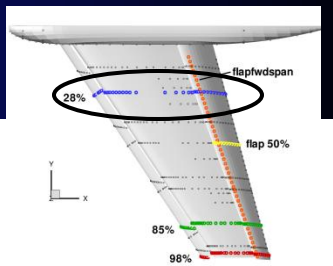


SURFACE PRESSURE AND SKIN FRICTION

What to watch for

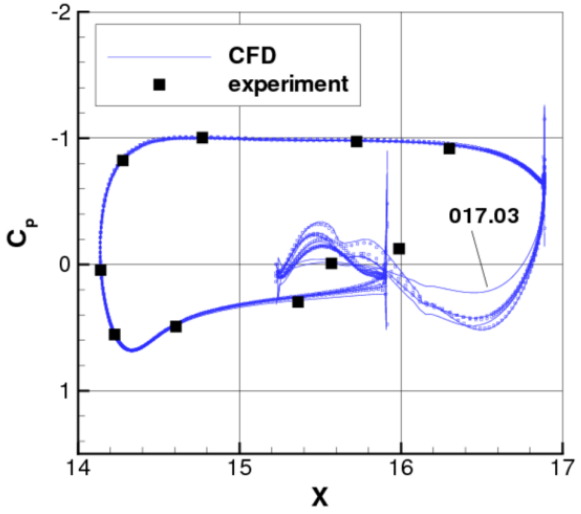
- Significant C_p variation among CFD results near T.E. of flap at outboard stations
- SST model showed greater tendency to separate on the flap than SA
- Tetrahedral grid exhibited greater grid sensitivity than a mixed element version of the same grid
- Different versions of the same model caused variability in the solution
- Wing tip region was problematic for CFD
  - All entries but one under-predicted suction levels
  - Thin-layer type approximation yielded particularly poor results
  - Turbulence model, grid also affected results
- Two entries that accounted for transition stood out

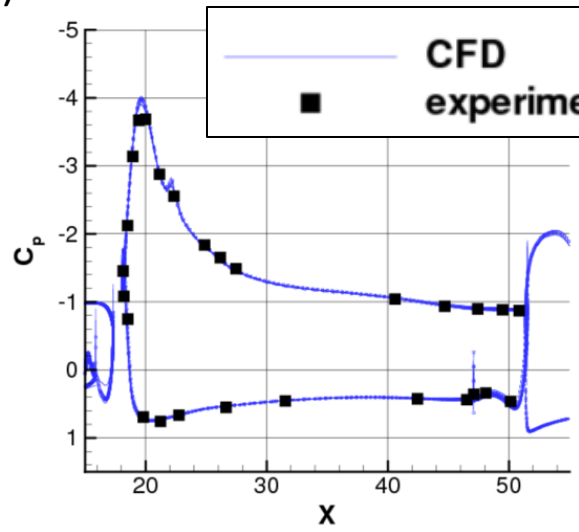
C_p at 28% span station

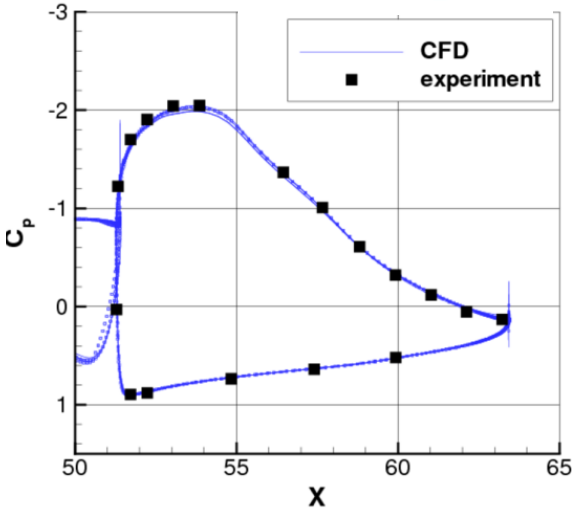


Alpha=13^0, configuration 1, SA only, fine grid

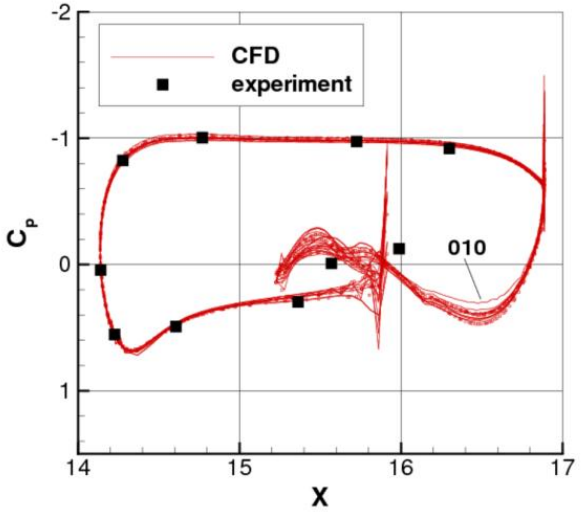
Structured (7 entries, 4 codes)

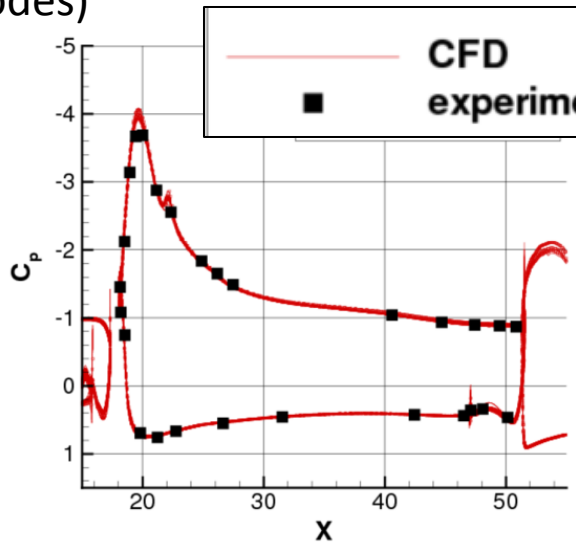


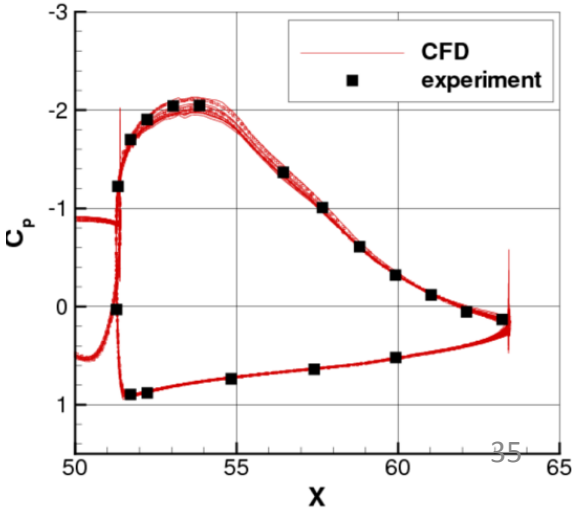




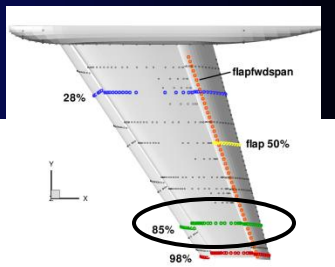
Unstructured (12 entries, 8 codes)





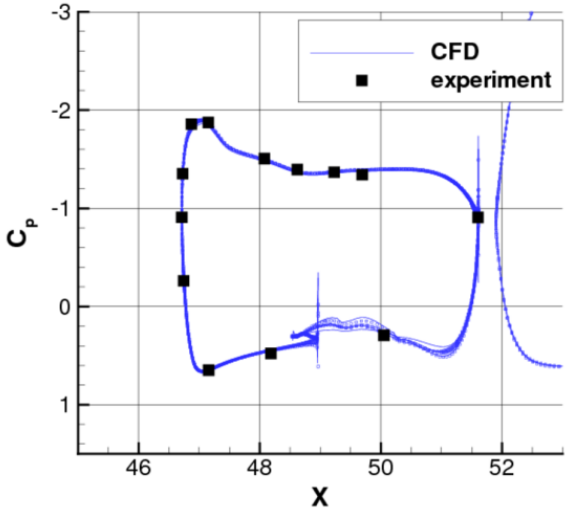


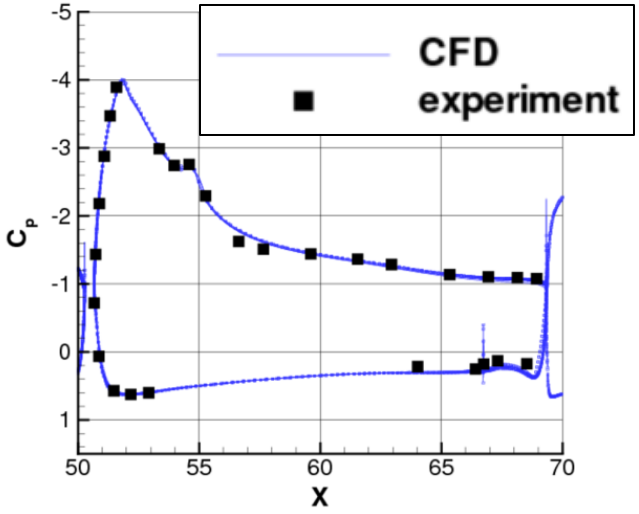
C_p at 85% span station

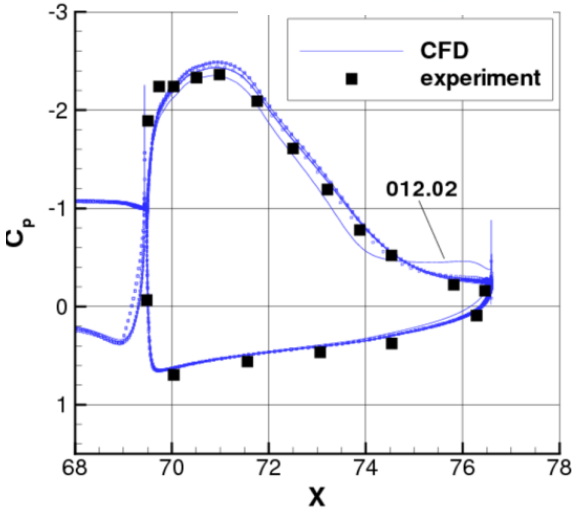


Alpha=13^0, configuration 1, SA only, fine grid

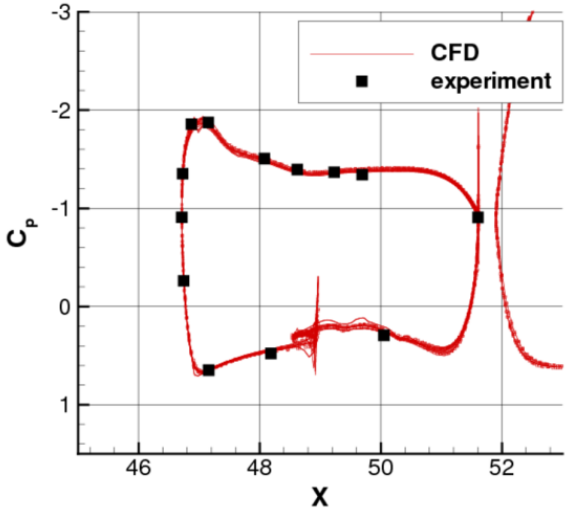
Structured (7 entries, 4 codes)

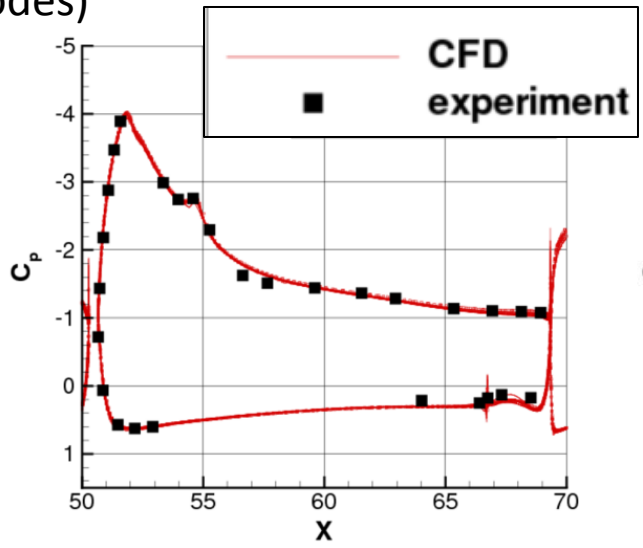


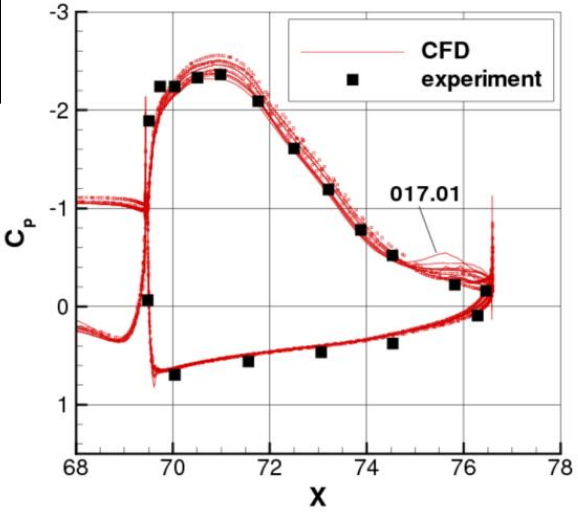




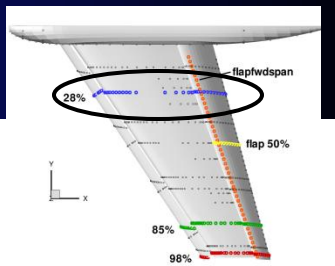
Unstructured (12 entries, 8 codes)





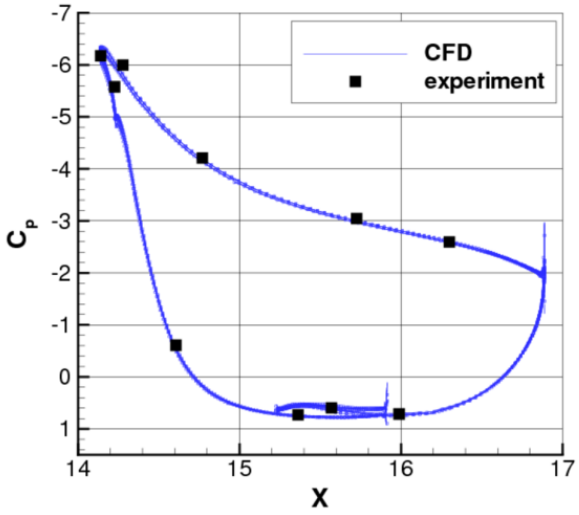


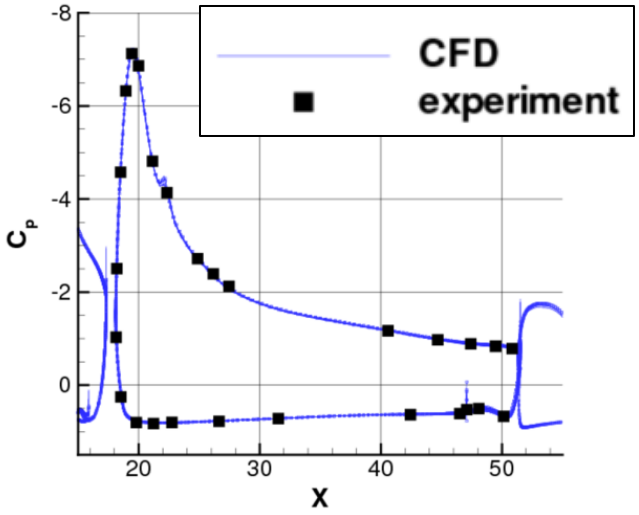
C_p at 28% span station

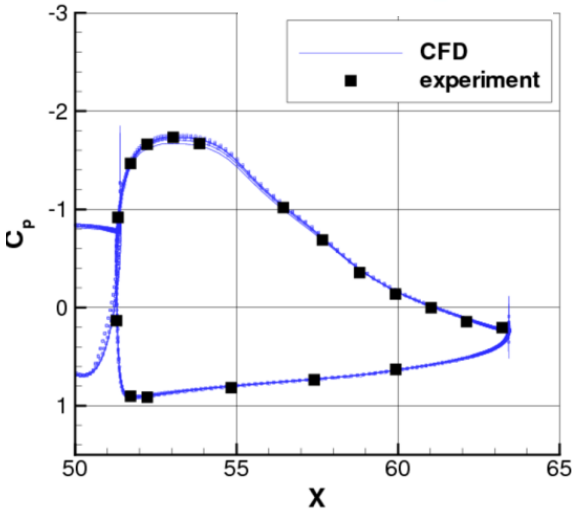


Alpha=28^0, configuration 1, SA only, fine grid

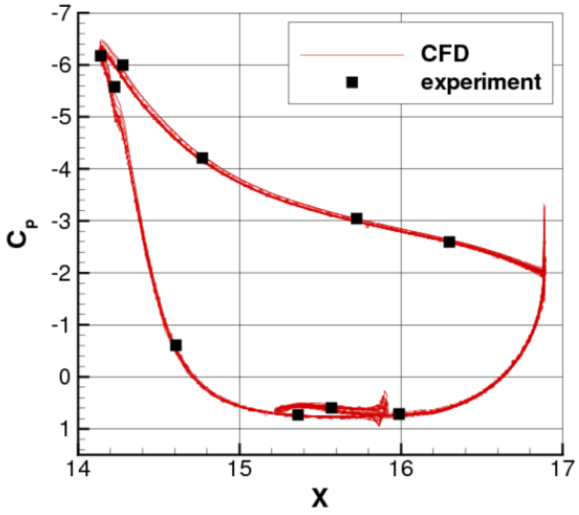
Structured (7 entries, 4 codes)

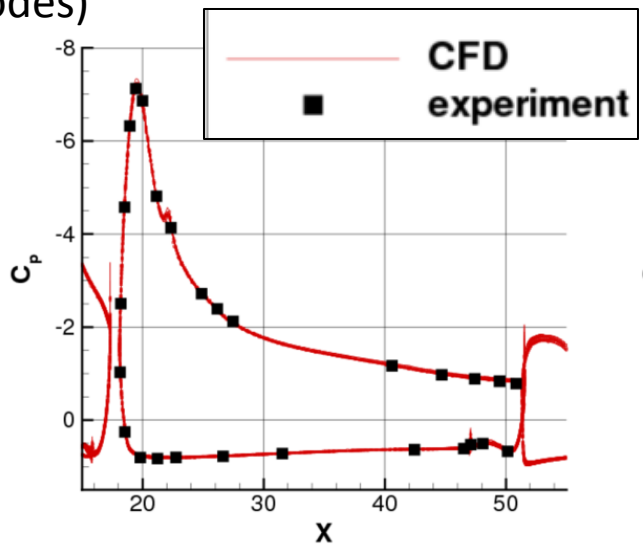


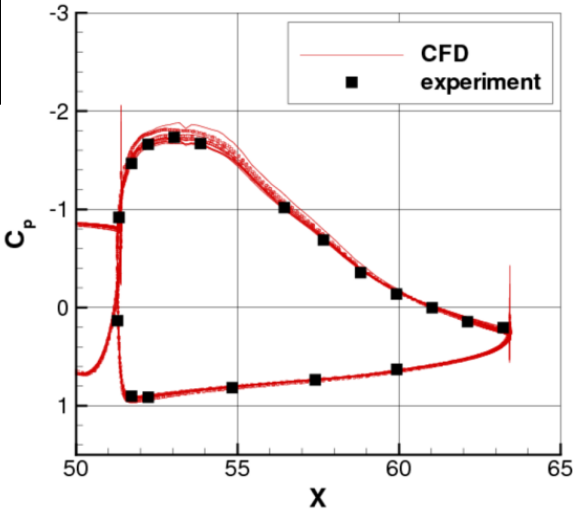




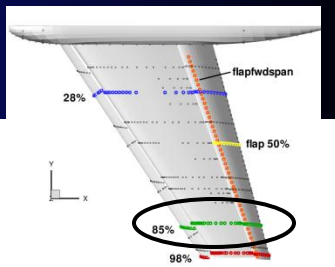
Unstructured (12 entries, 8 codes)





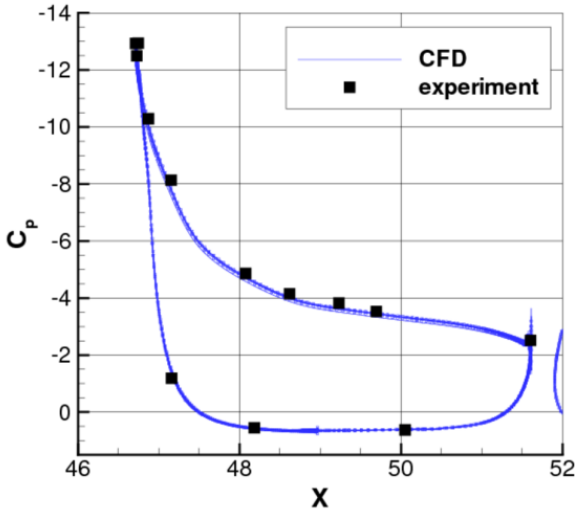


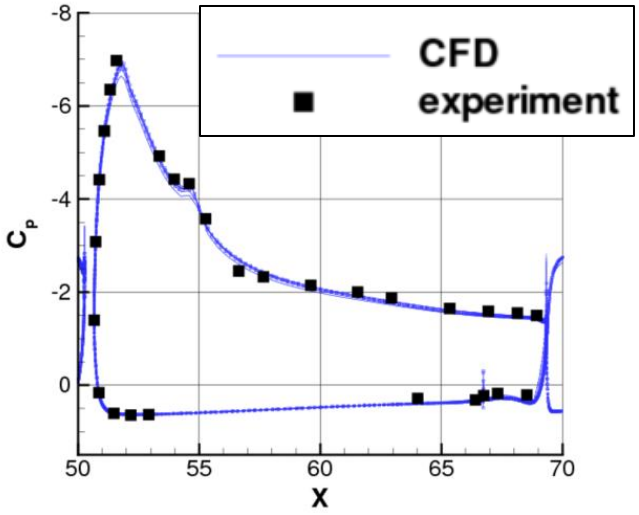
C_p at 85% span station

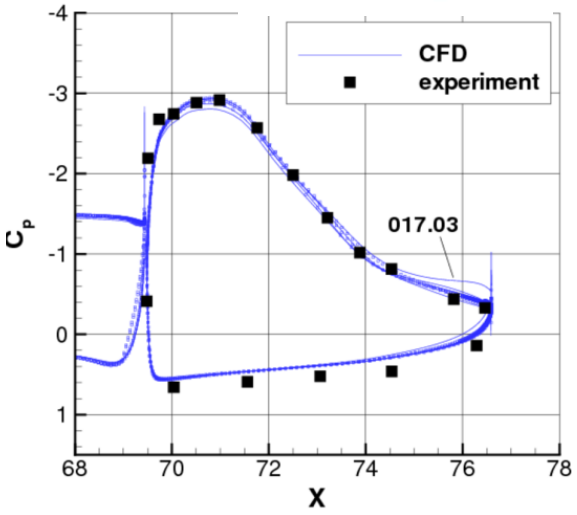


Alpha=28^0, configuration 1, SA only, fine grid

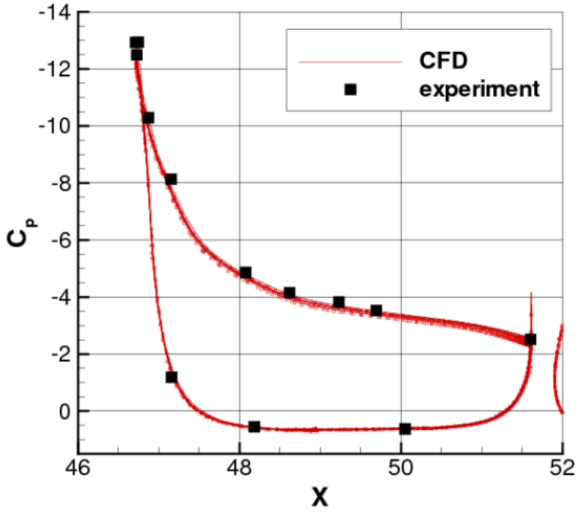
Structured (7 entries, 4 codes)

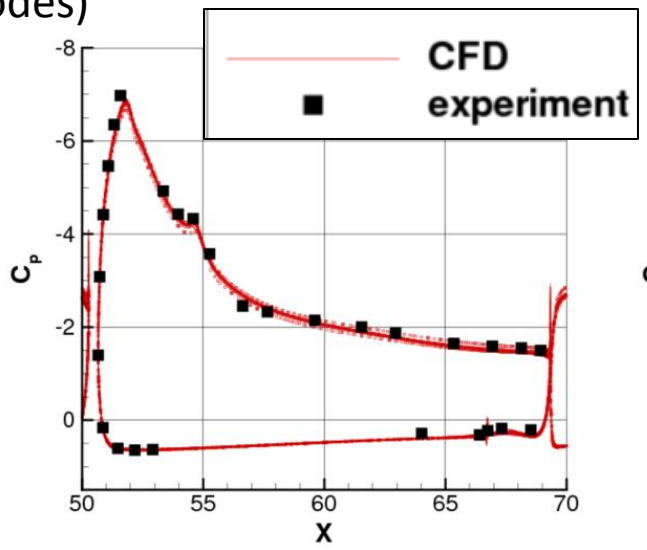


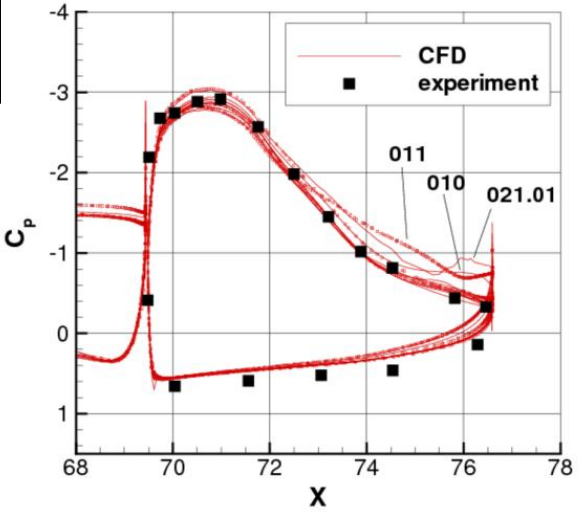




Unstructured (12 entries, 8 codes)



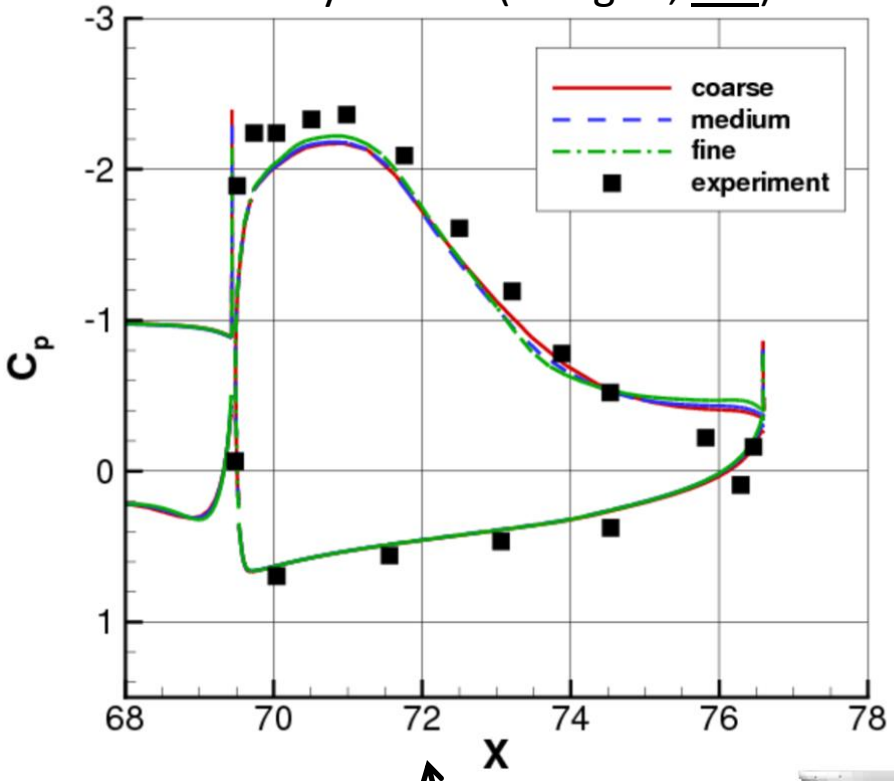




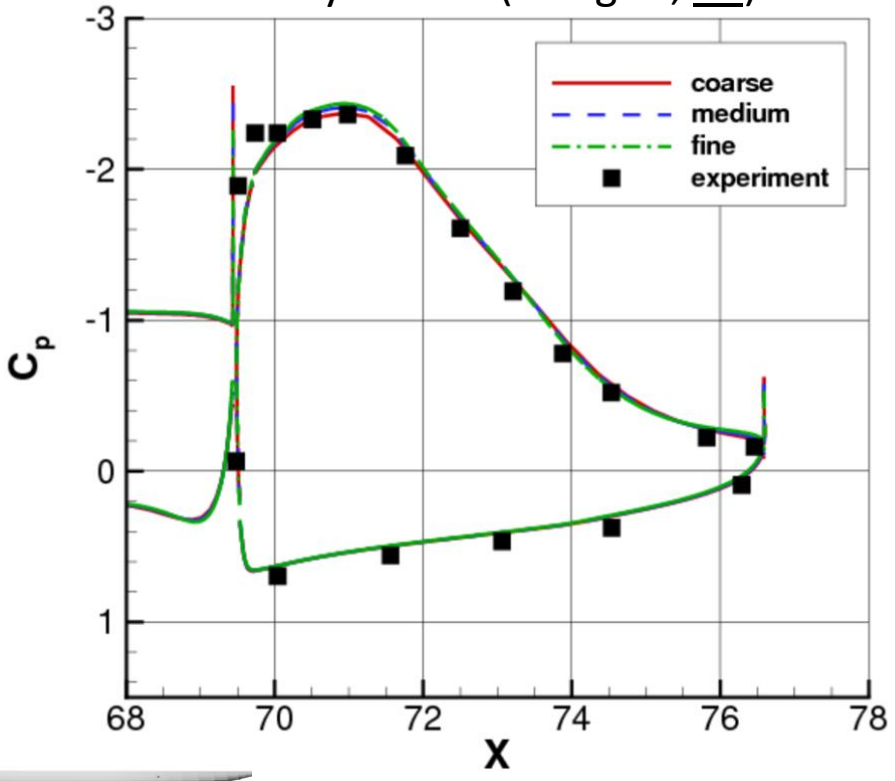
Sampling of C_p at 85% flap station

Alpha=13^0, configuration 1

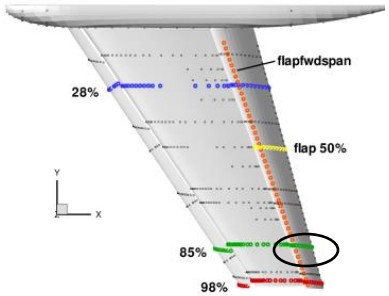
Entry 017.02 (SX1 grid, SST)



Entry 017.03 (SX1 grid, SA)



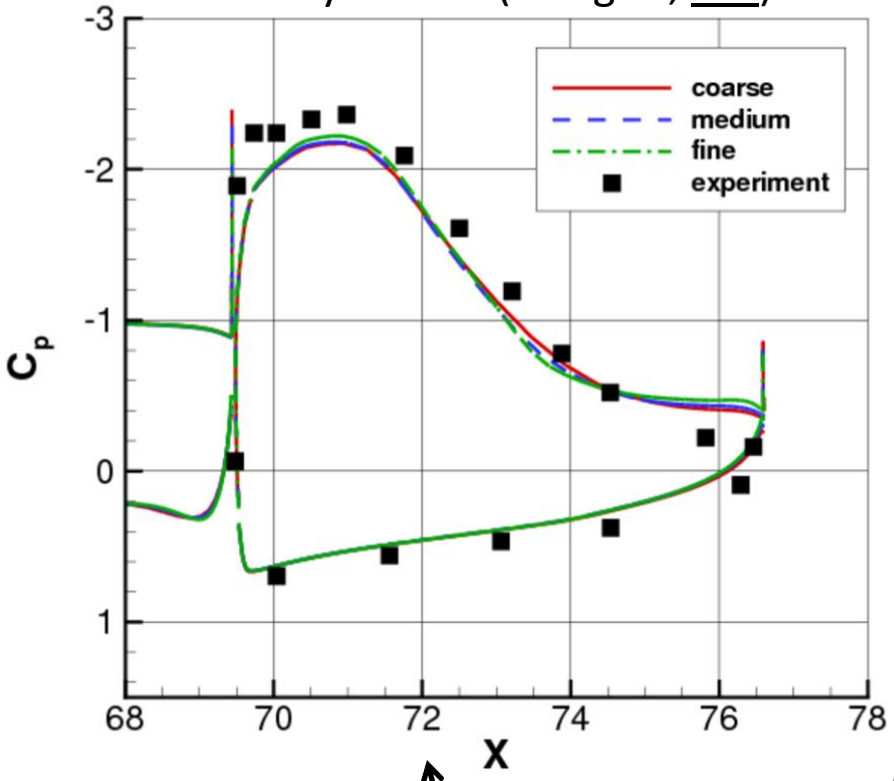
Most other SST results were similar



Sampling of C_p at 85% flap station

Alpha=13^0, configuration 1

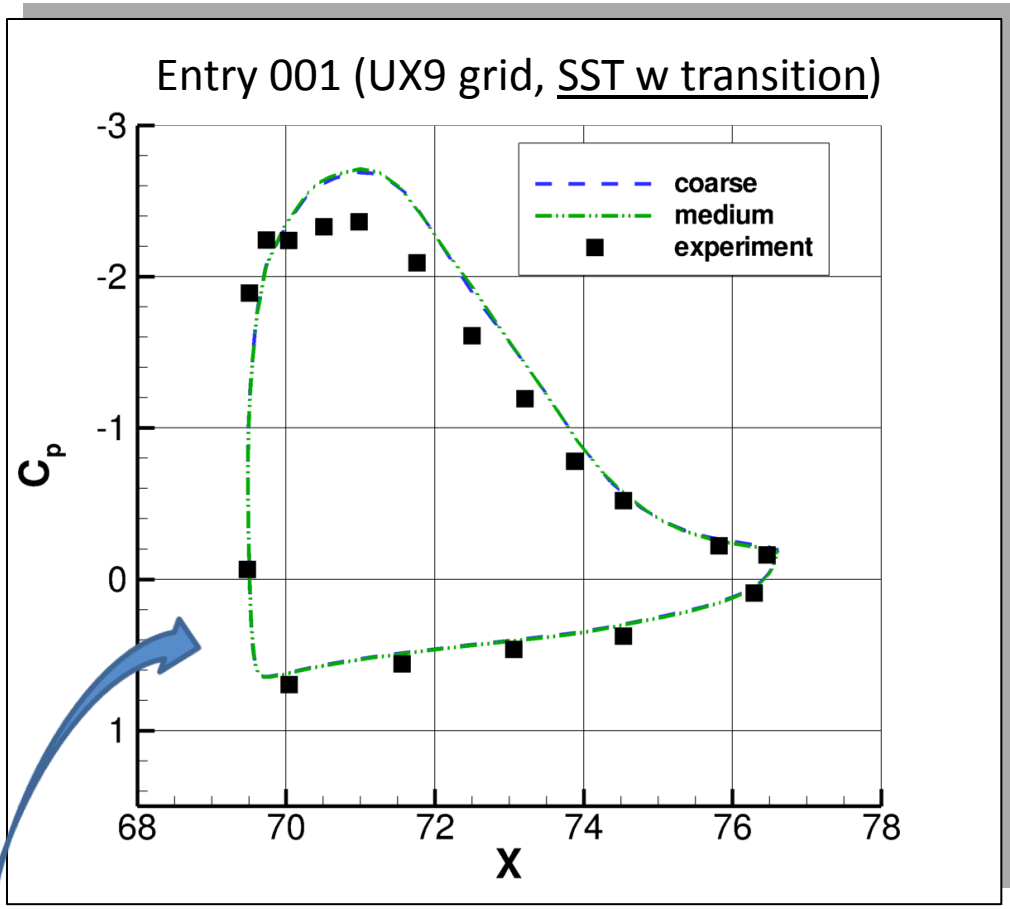
Entry 017.02 (SX1 grid, SST)



Most other SST results were similar

With the exception of 001 (SST with transition)

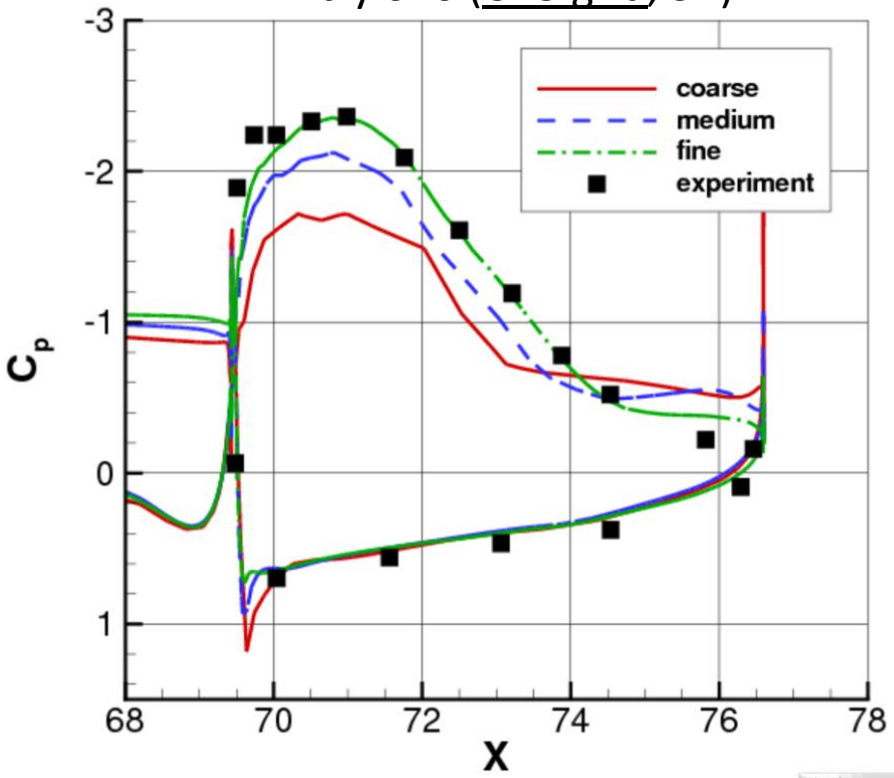
Entry 001 (UX9 grid, SST w transition)



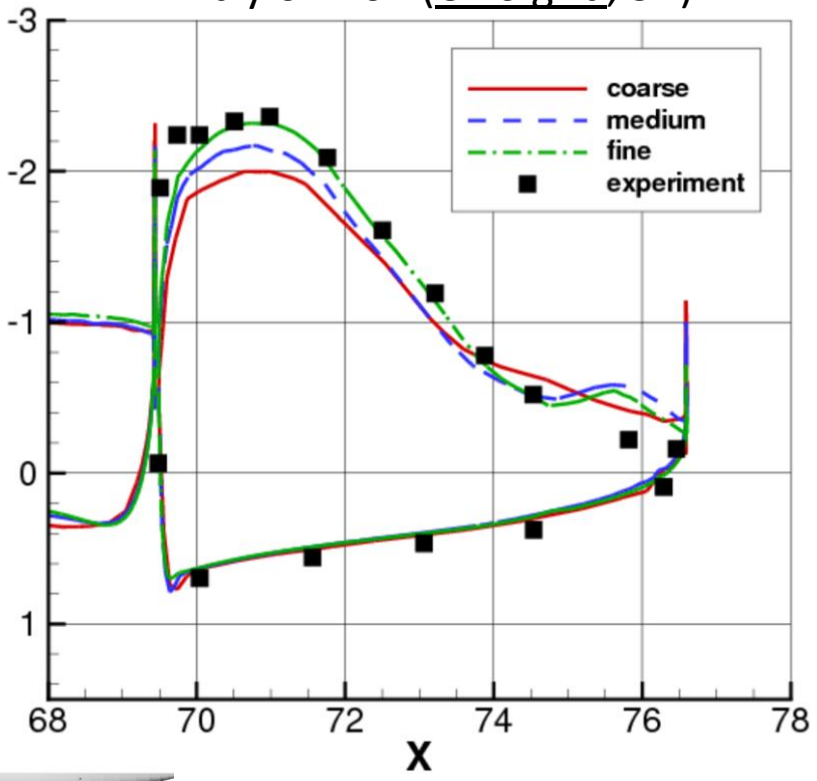
Sampling of C_p at 85% flap station

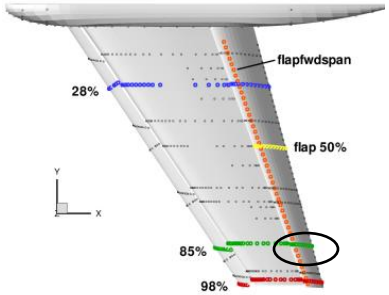
Alpha=13^0, configuration 1

Entry 016 (UT5 grid, SA)



Entry 017.01 (UH6 grid, SA)

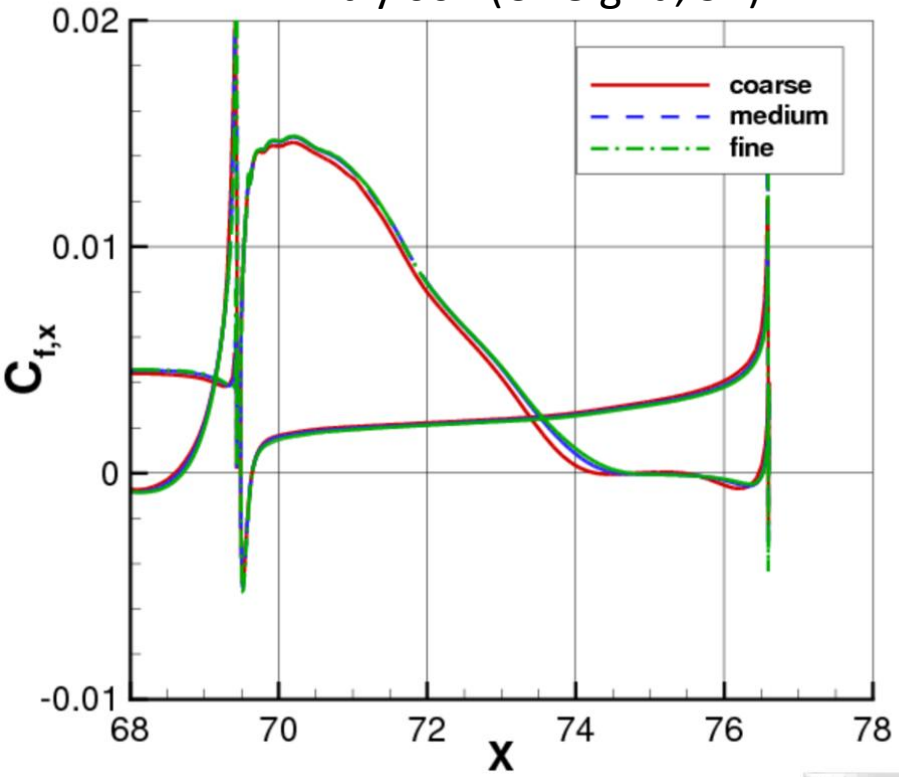




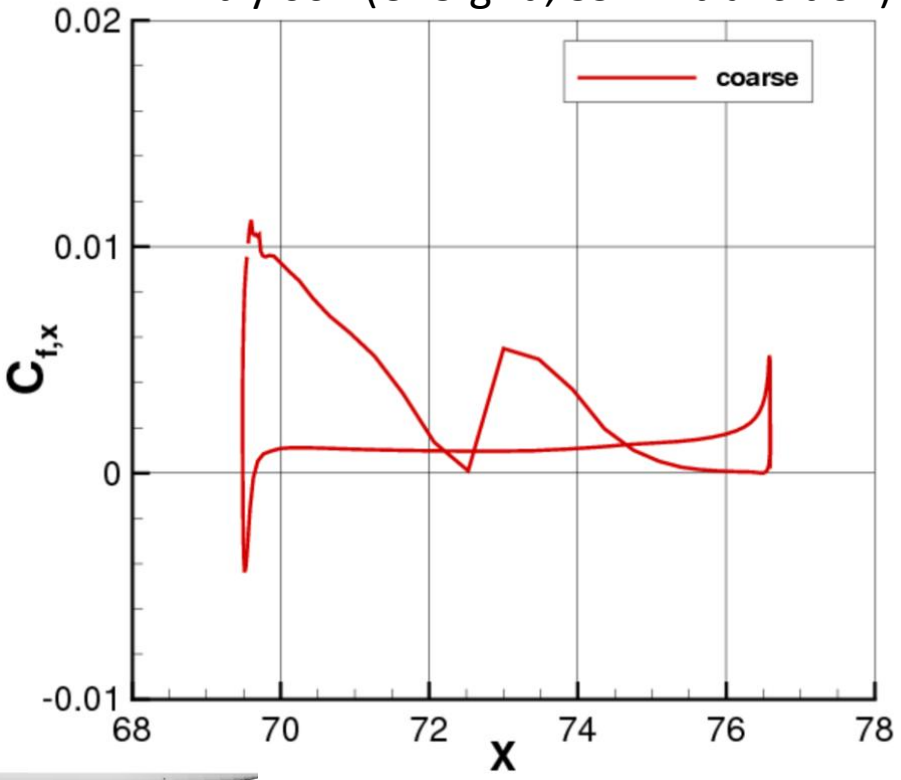
Sampling of $C_{f,x}$ at 85% flap station

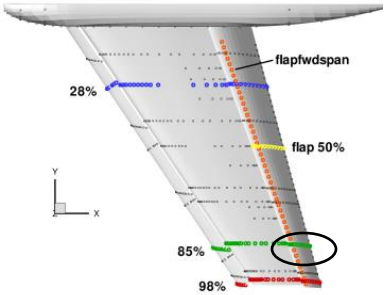
Alpha=13^0, configuration 1

Entry 007 (UH8 grid, SA)



Entry 001 (UX9 grid, SST w transition)

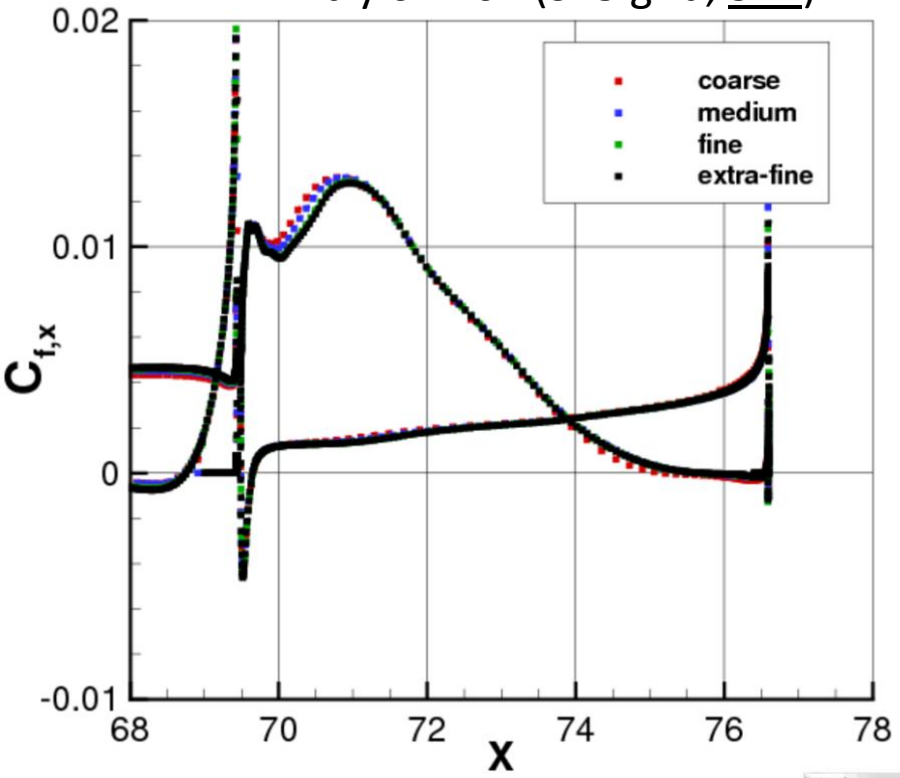




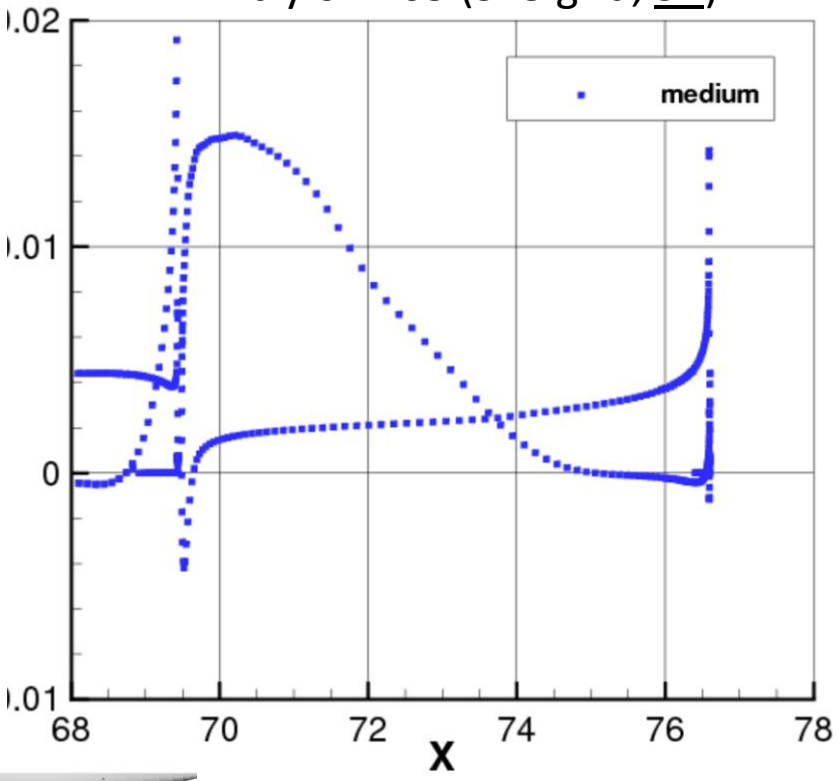
Sampling of $C_{f,x}$ at 85% flap station

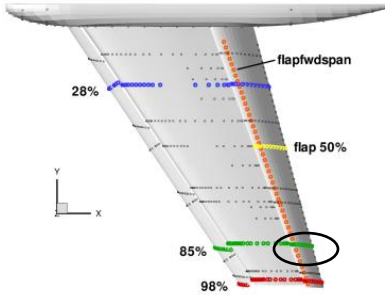
Alpha=13^0, configuration 1

Entry 014.01 (SX3 grid, SA*)



Entry 014.05 (SX3 grid, SA)



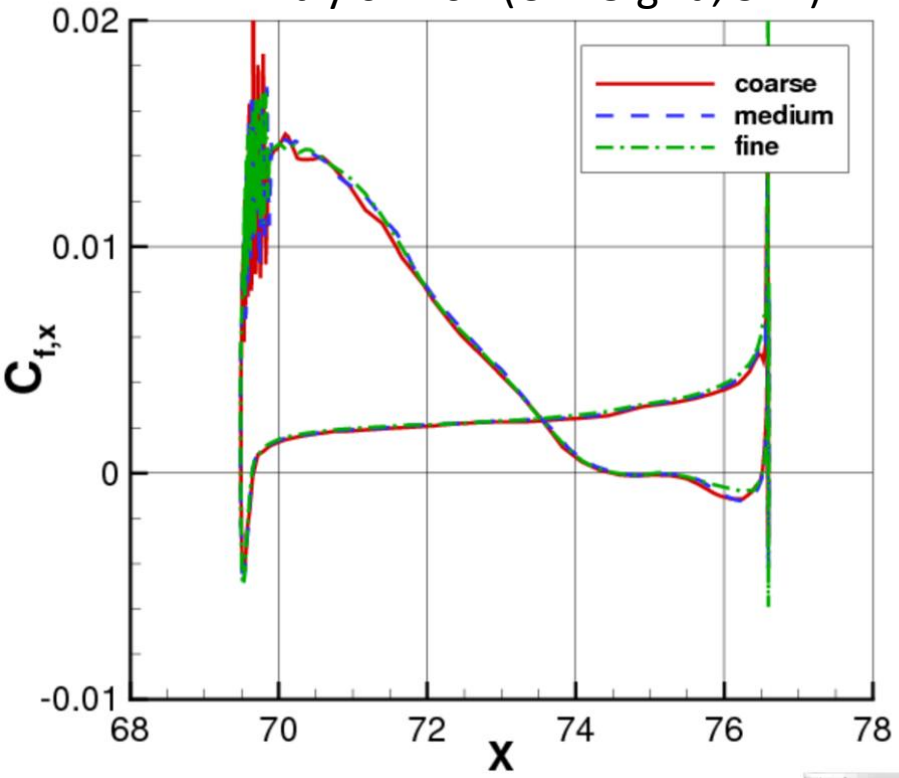


SA* = SA-fv3, known to delay onset of turbulence compared to SA

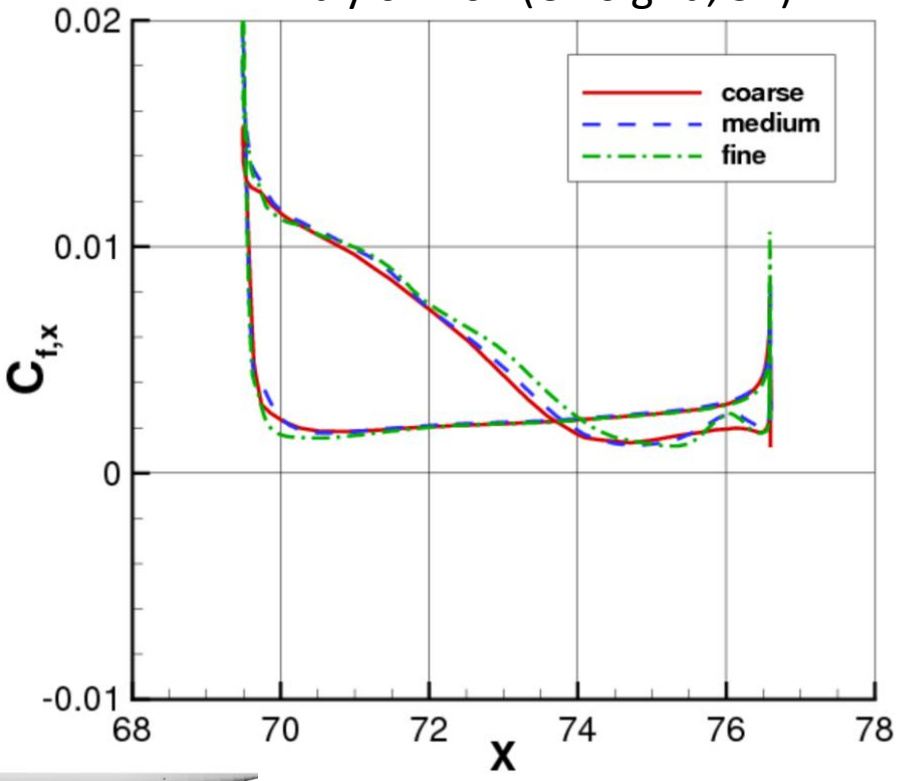
Sampling of $C_{f,x}$ at 85% flap station

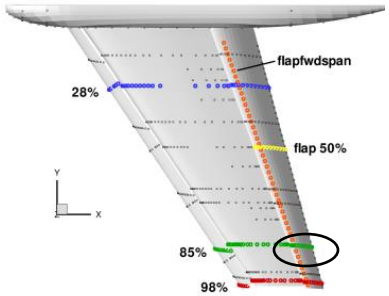
Alpha=13^0, configuration 1

Entry 012.01 (UH15 grid, SA*)

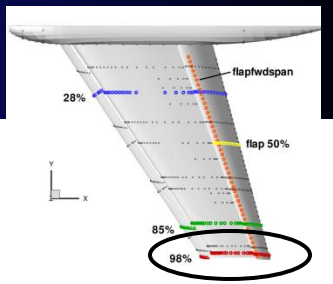


Entry 021.01 (UH6 grid, SA)



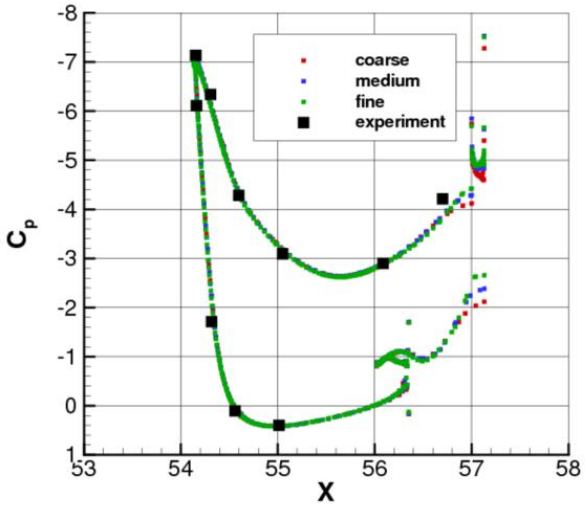


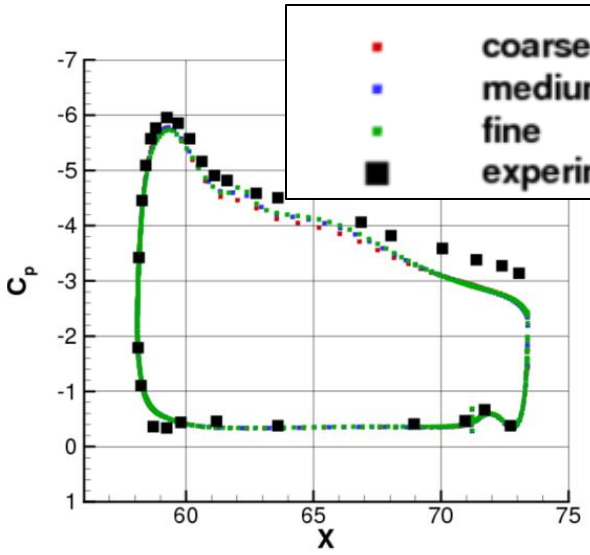
Sampling of Cp at 98% span

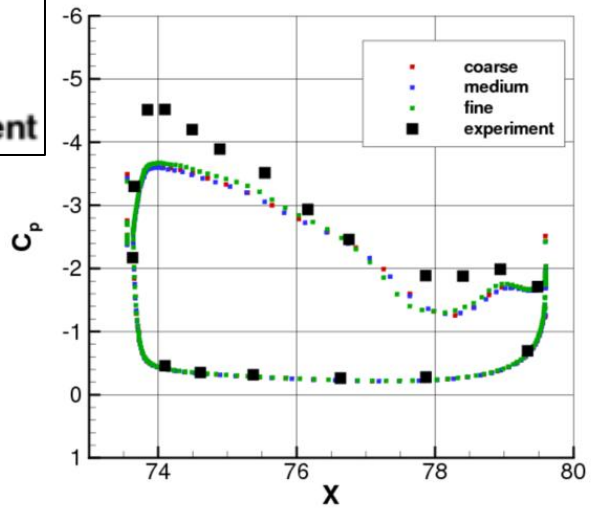


Alpha=28^0, configuration 1

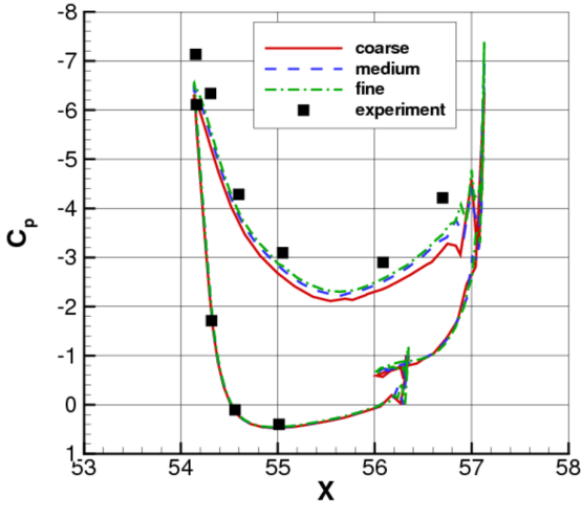
Entry 018 (full N-S)

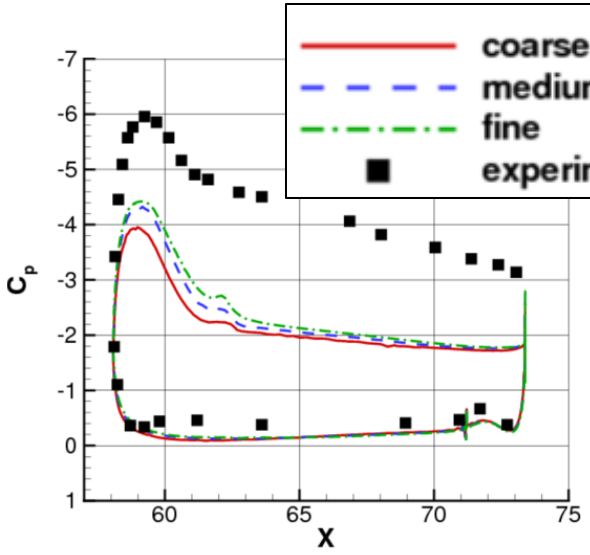


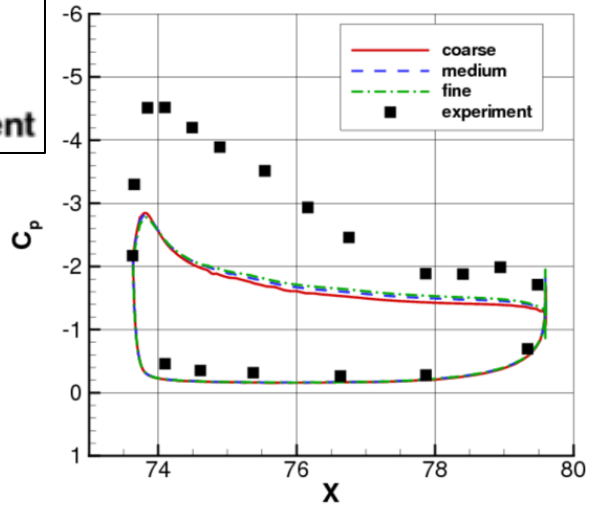




Entry 010 (thin-layer N-S)



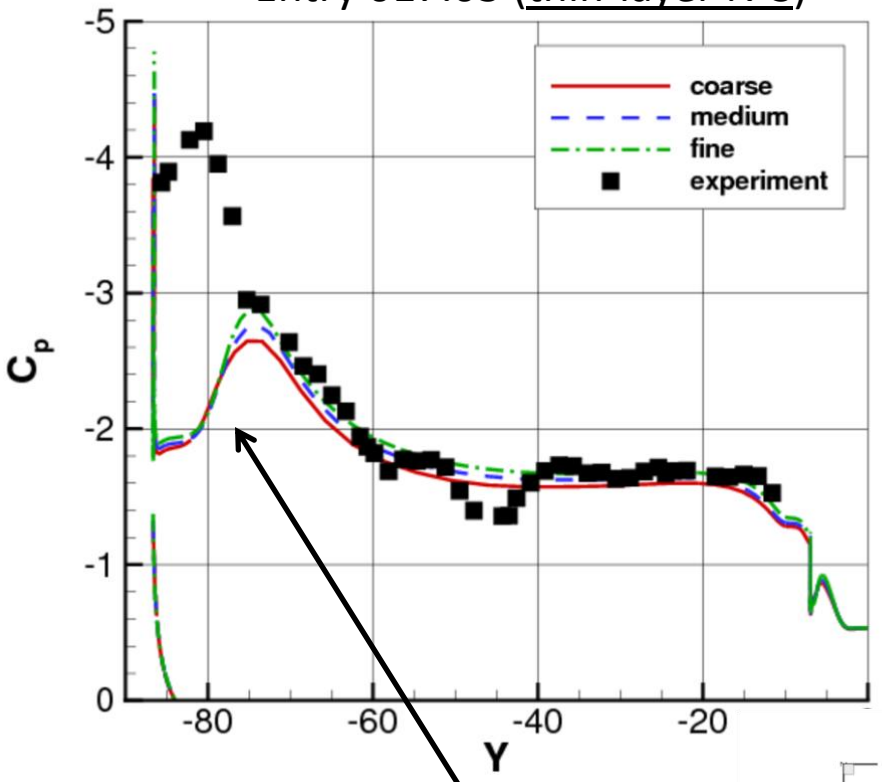




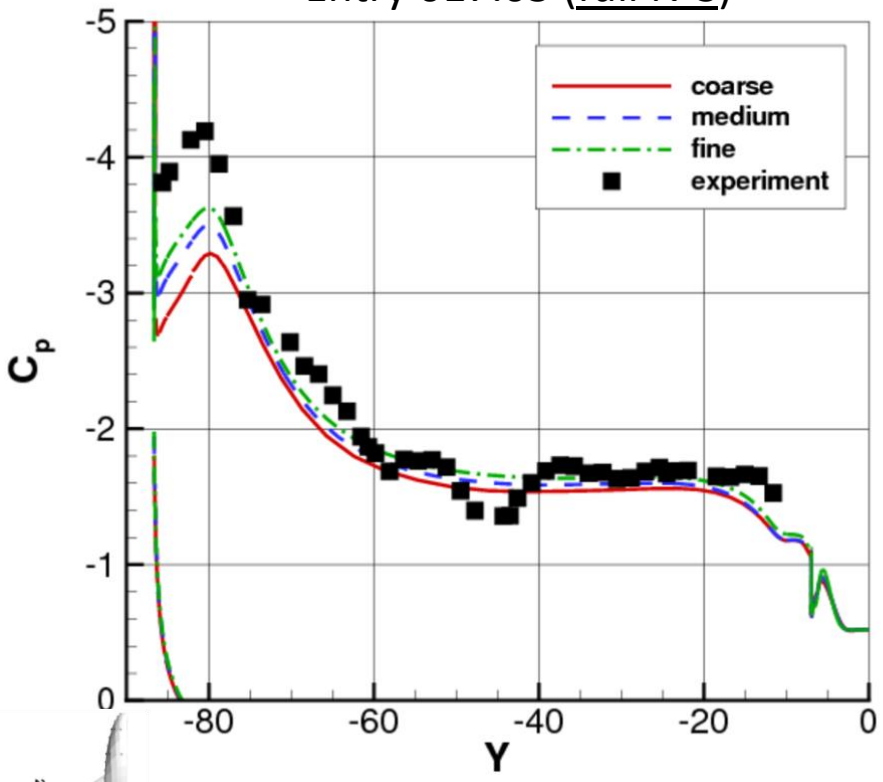
Sampling of Cp along flap

Alpha=28^0, configuration 1
CFL3D, SX1 grid, SA

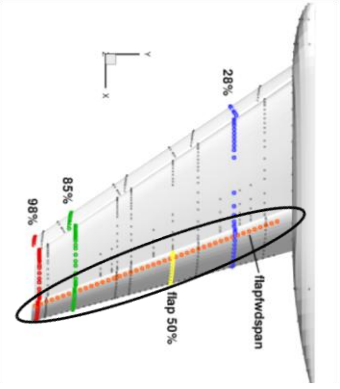
Entry 017.03 (thin-layer N-S)



Entry 017.05 (full N-S)



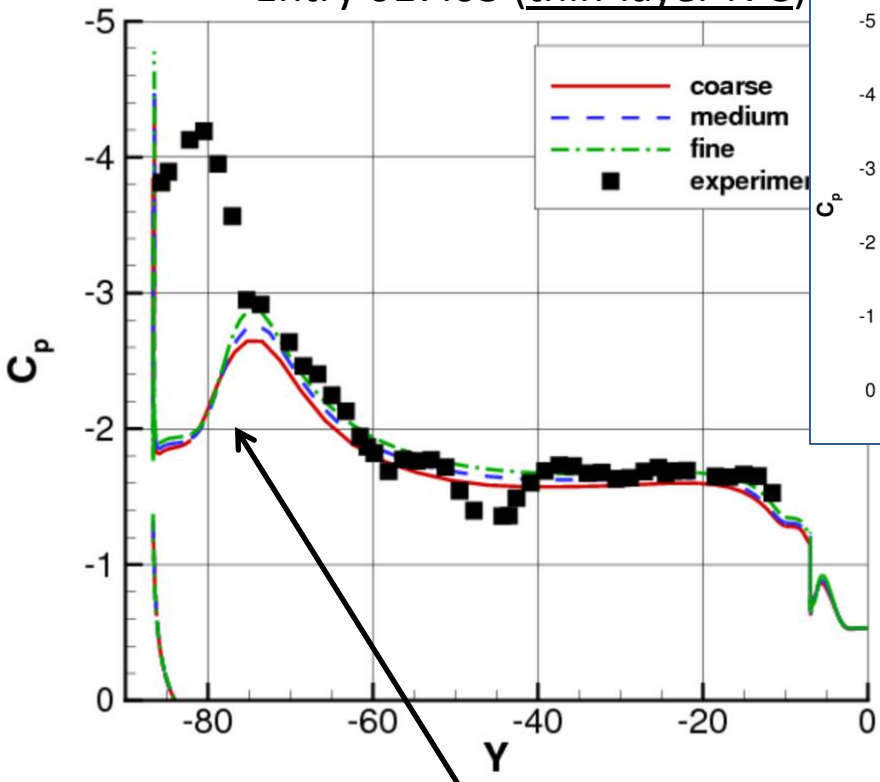
Other thin-layer results were similar



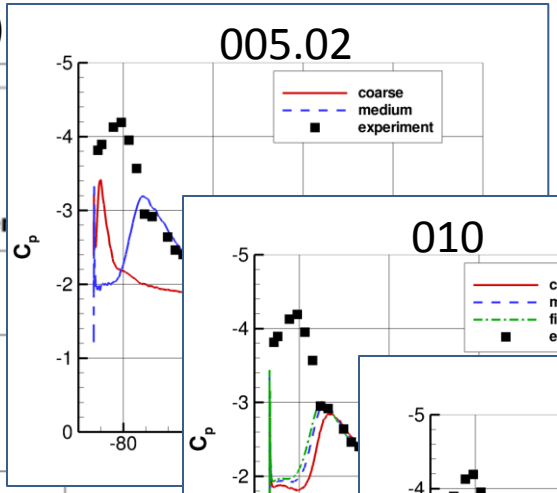
Sampling of Cp along flap

Alpha=28^0, configuration 1
CFL3D, SX1 grid, SA

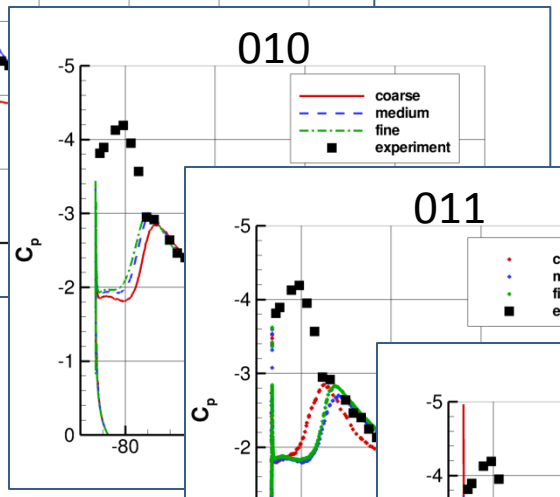
Entry 017.03 (thin-layer N-S)



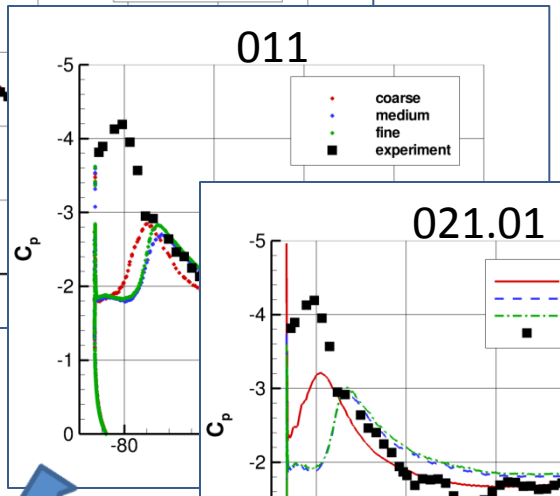
005.02



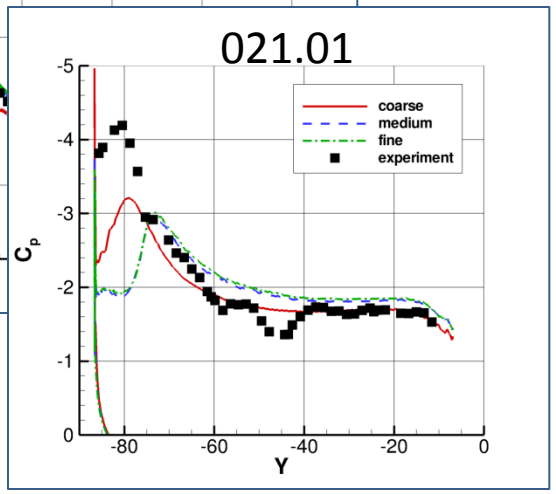
010



011



021.01

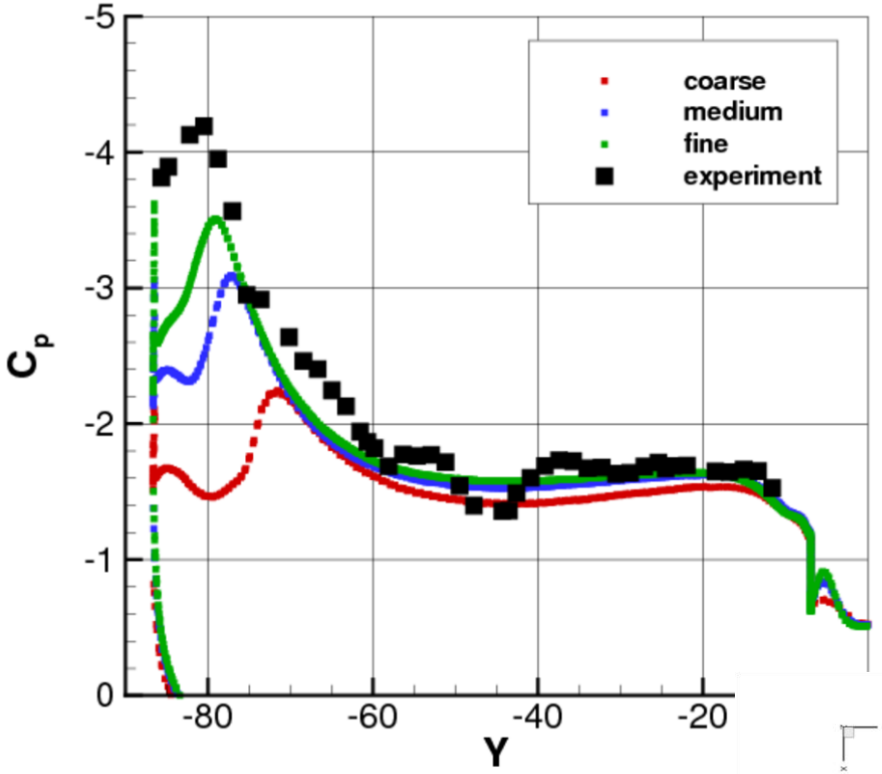


Other thin-layer results were similar

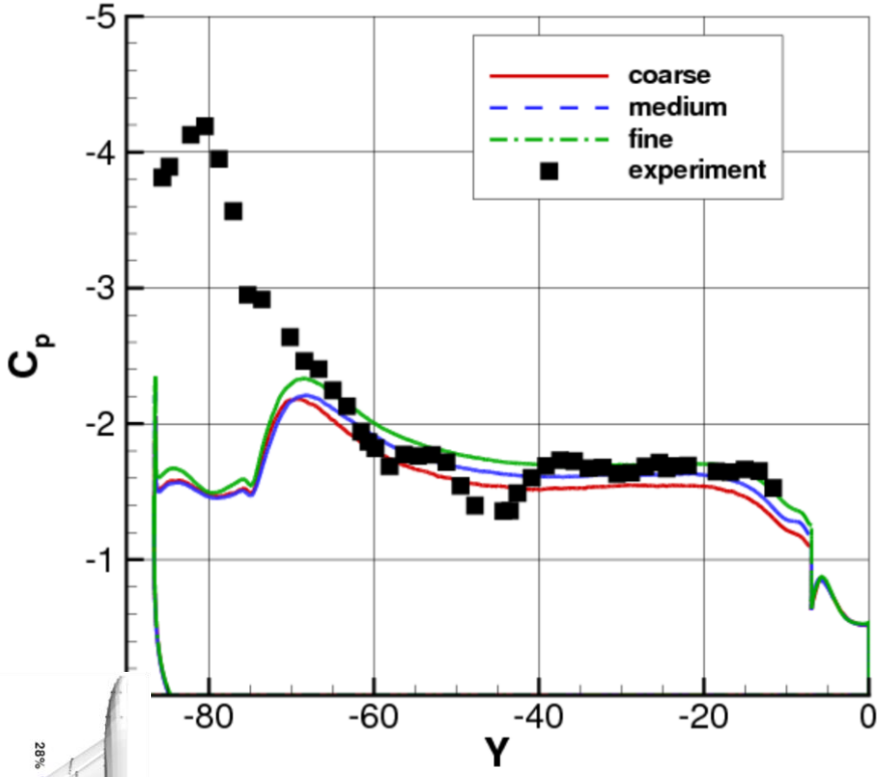
Sampling of Cp along flap

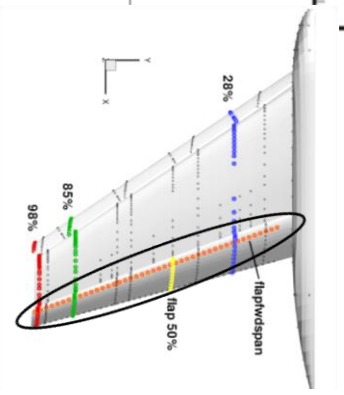
Alpha=28^0, configuration 1
CFD++, k-epsilon-type

Entry 013.02 (UT5 grid, $k-\varepsilon-R_t$)



Entry 002 (UH13 grid, realizable $k-\varepsilon$)

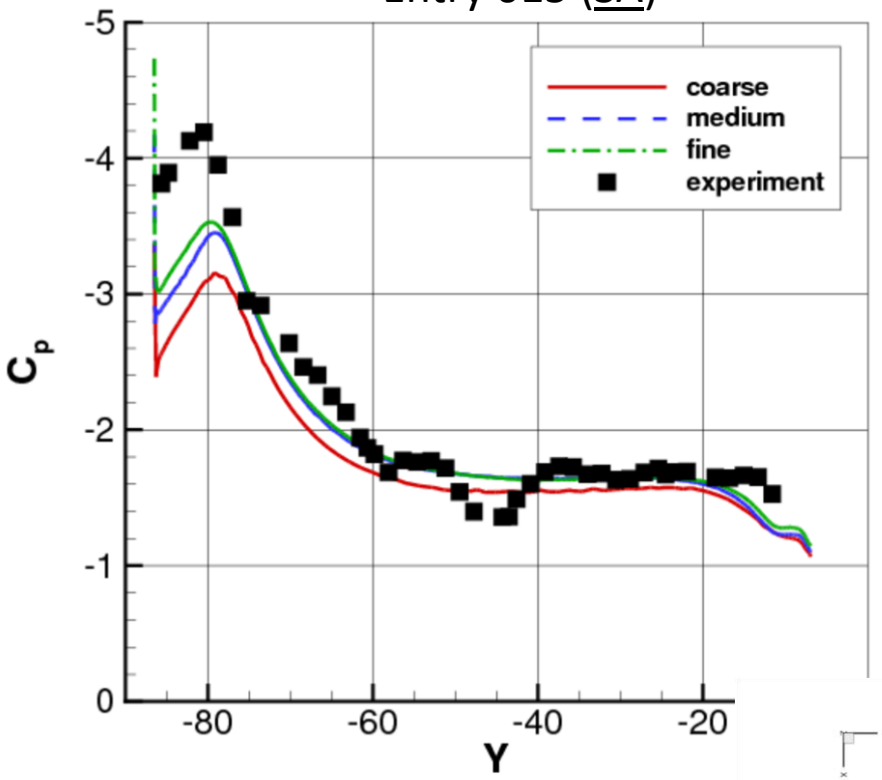




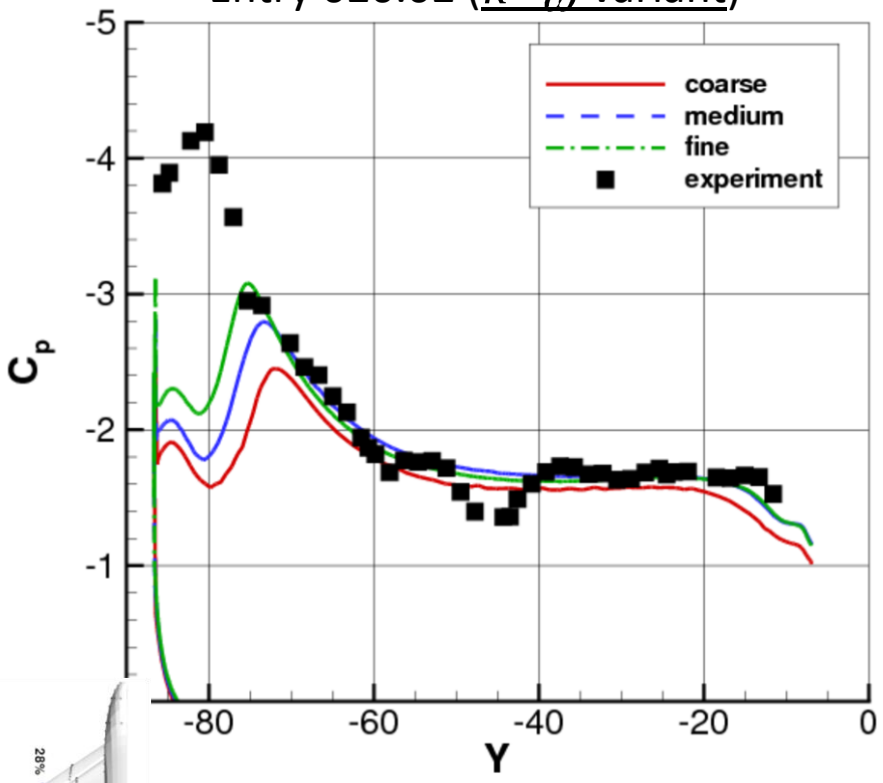
Sampling of Cp along flap

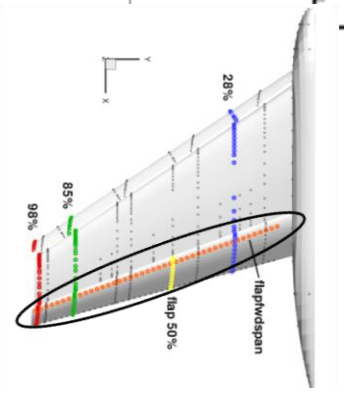
Alpha=28^0, configuration 1
USM3D, UT4 grid

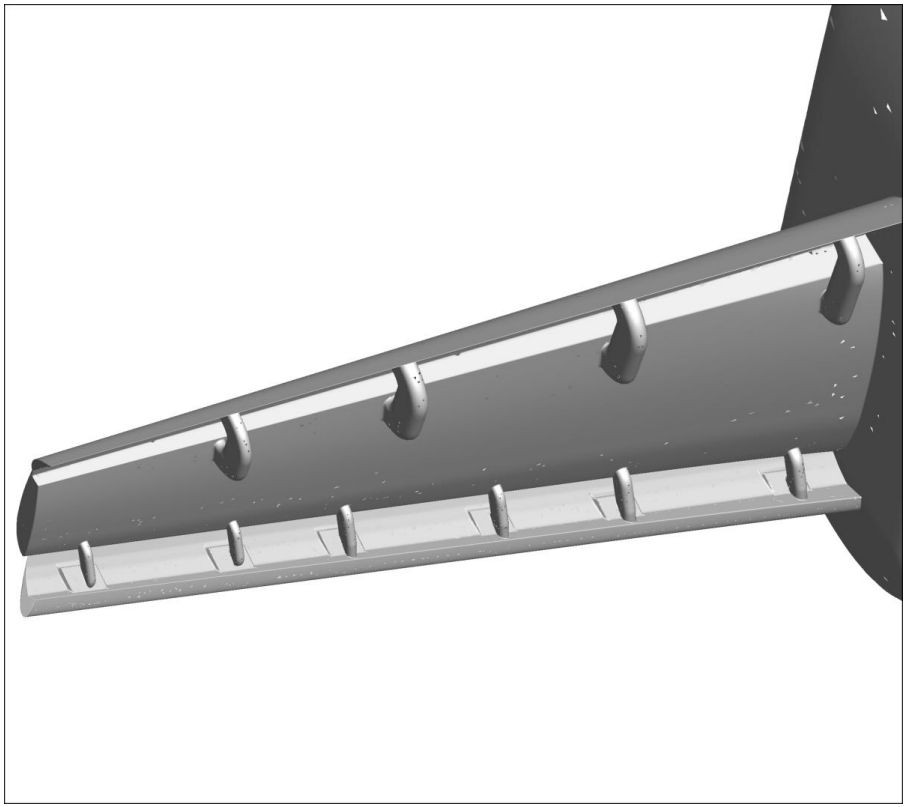
Entry 015 (SA)

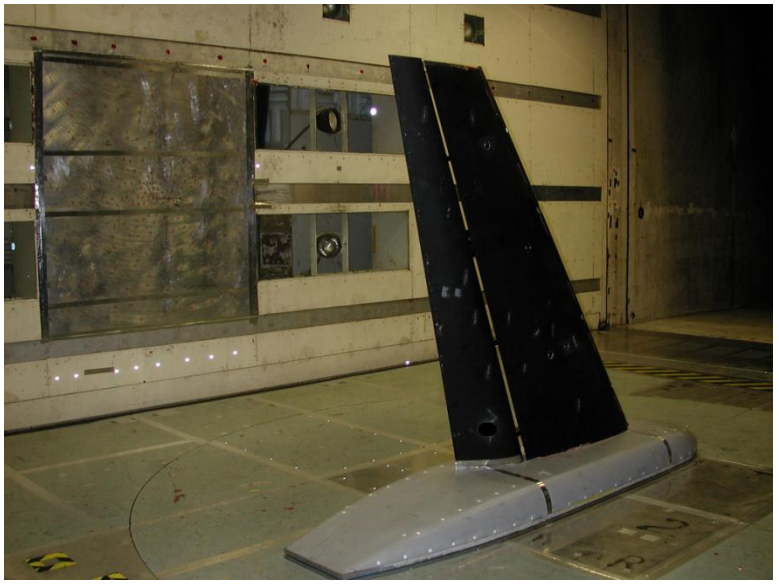


Entry 020.02 ($k-\omega$ variant)









EFFECT OF SUPPORT BRACKETS

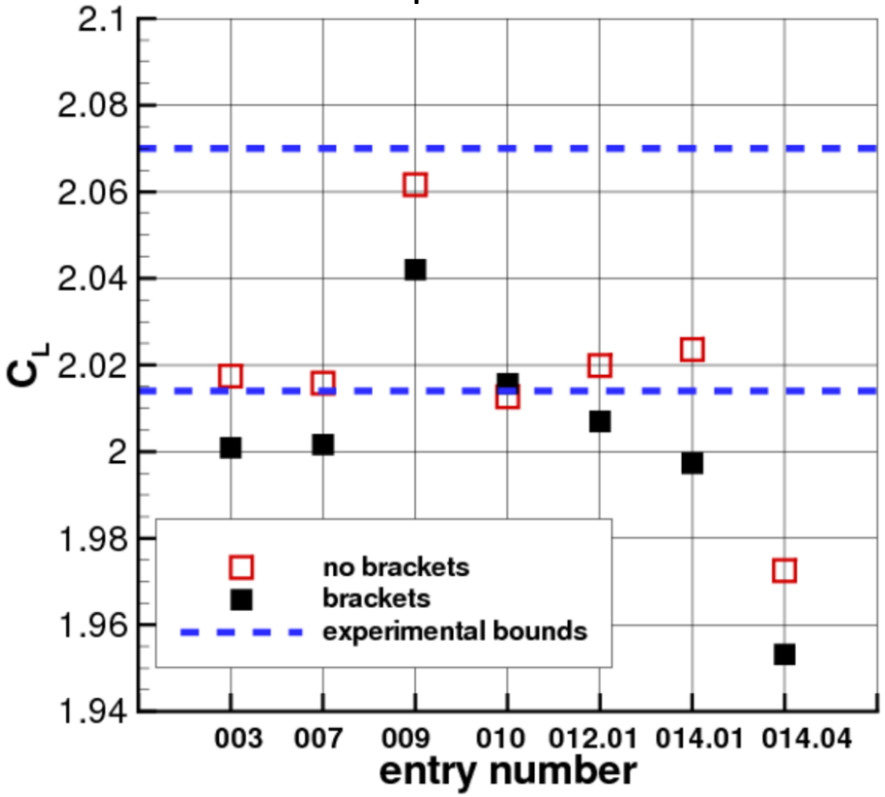
What to watch for

- Including support brackets
  - Decreased lift
  - Yielded improved C_p comparisons at some stations

Effect of support brackets on C_L

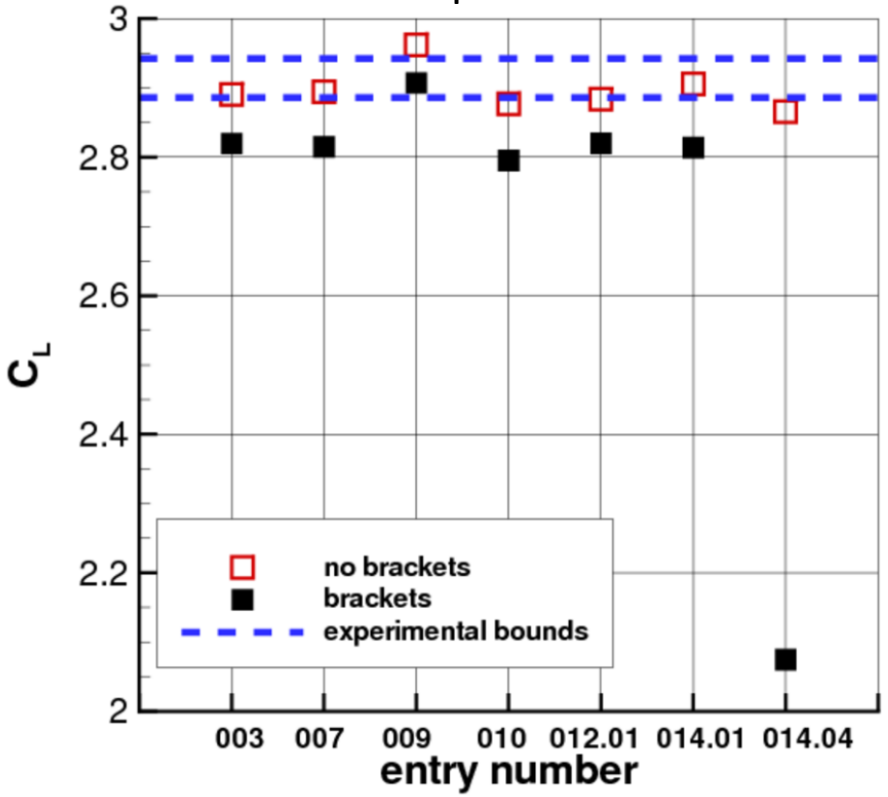
Configuration 1, medium grids*

Alpha = 13°



Avg Delta C_L = 0.015 decrease w brackets

Alpha = 28°



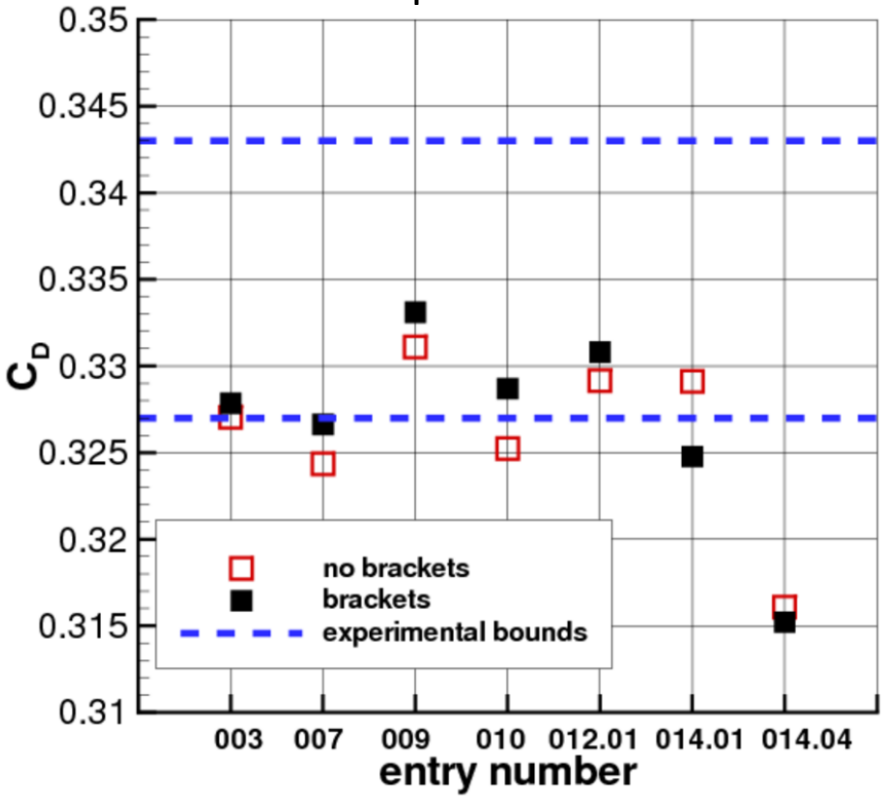
Avg Delta C_L = 0.074 decrease w brackets (ignoring aberrant entry 014.04)

* except entry 009 on F

Effect of support brackets on C_D

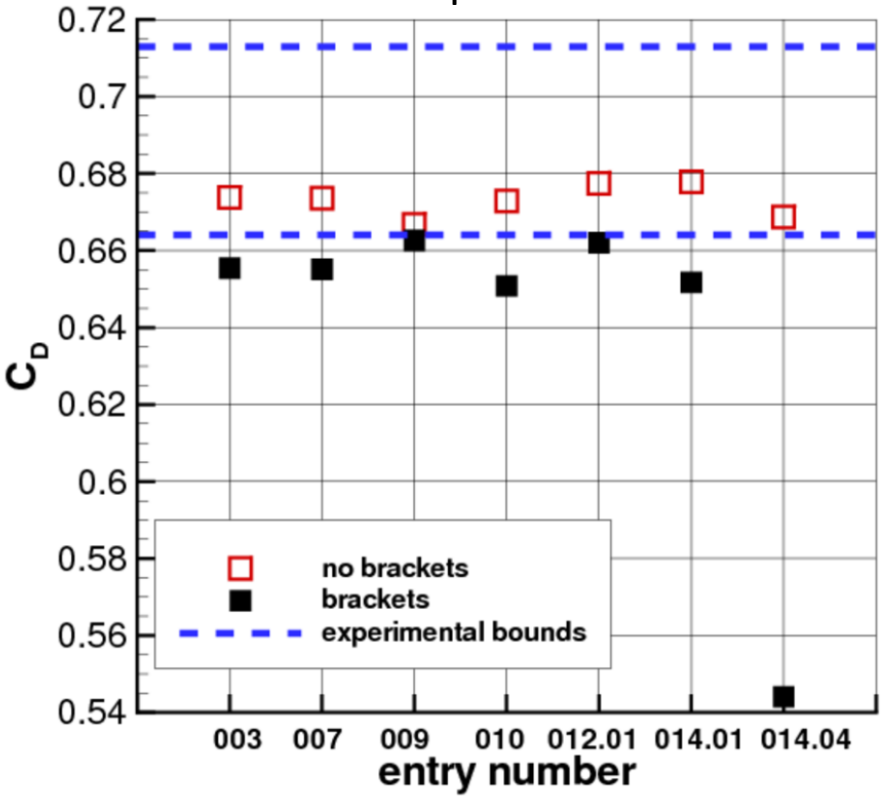
Configuration 1, medium grids*

Alpha = 13°



Trend unclear

Alpha = 28°



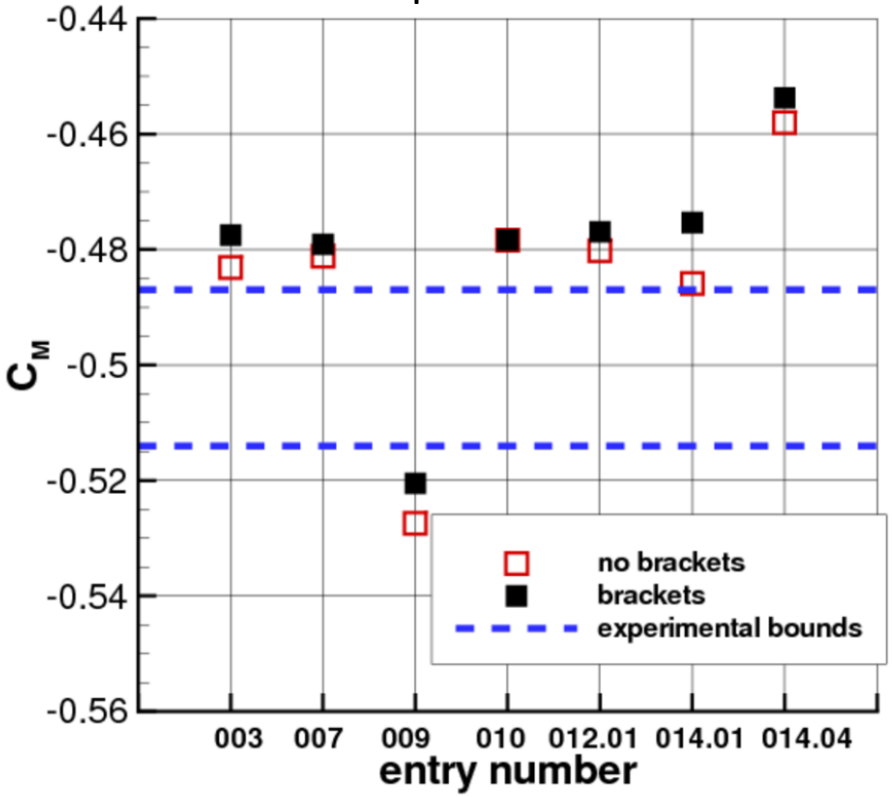
Avg Delta C_D = 0.0174 decrease w brackets (ignoring aberrant entry 014.04)

* except entry 009 on F

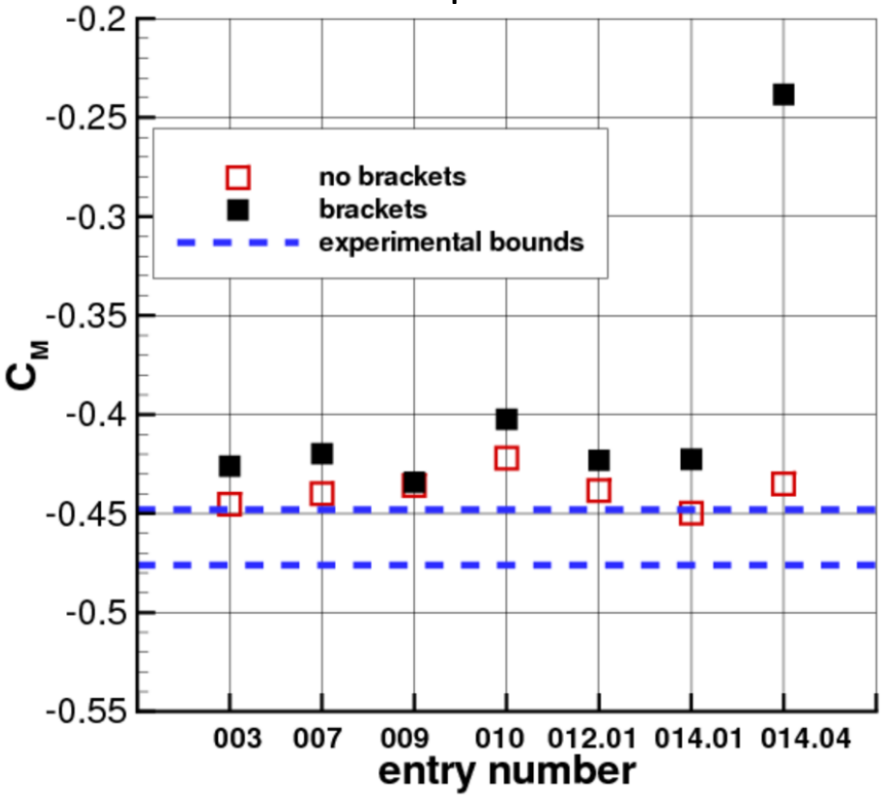
Effect of support brackets on C_M

Configuration 1, medium grids*

Alpha = 13°



Alpha = 28°

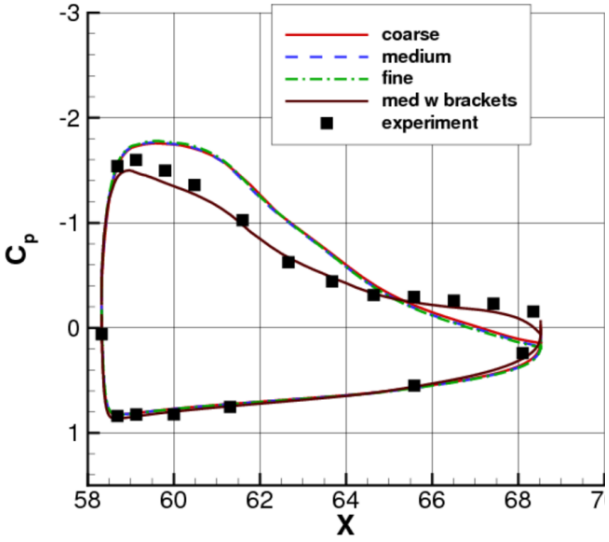


* except entry 009 on F

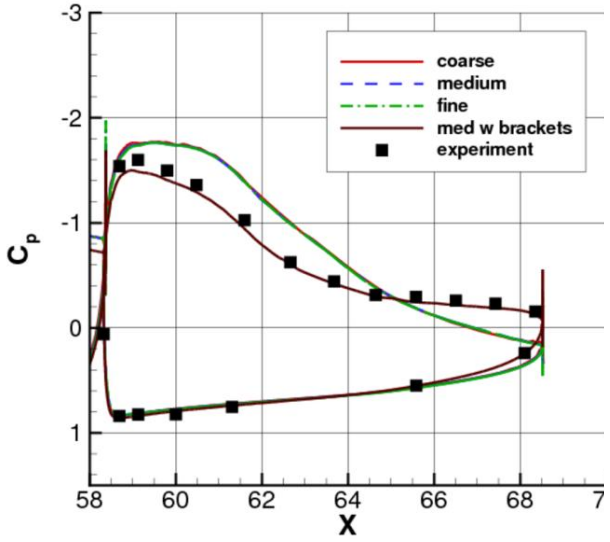
Effect of brackets at 50% flap station

Alpha=28^0, configuration 1

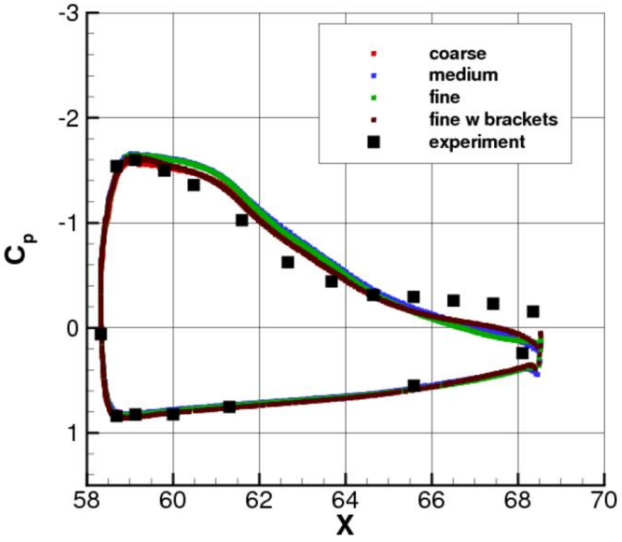
Entry 003.01



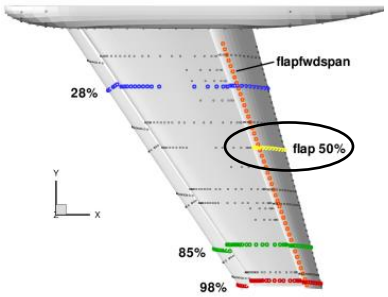
Entry 007



Entry 009



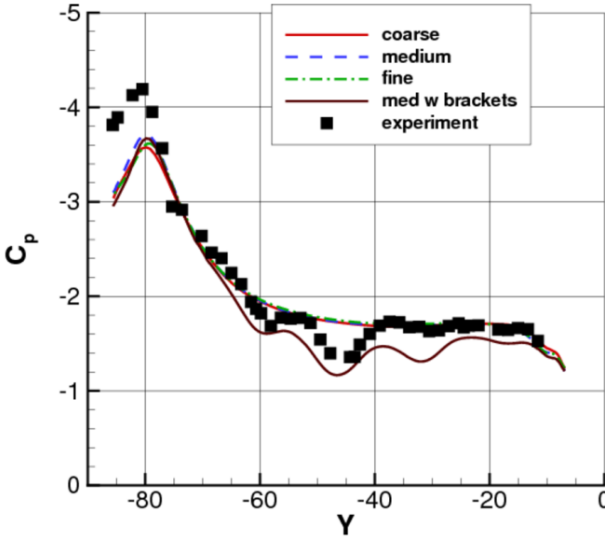
Big improvement: 003.01, 007, 010, 014.01
Small improvement: 012.01
Little effect: 009
Aberrant result w brackets: 014.04



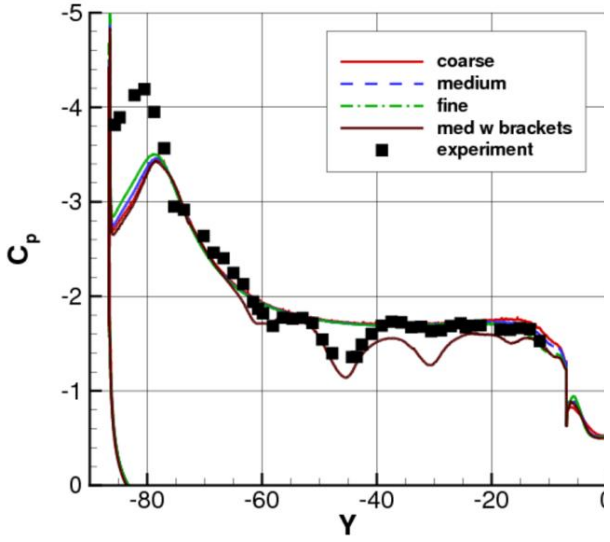
Effect of brackets along flap

Alpha=28^0, configuration 1

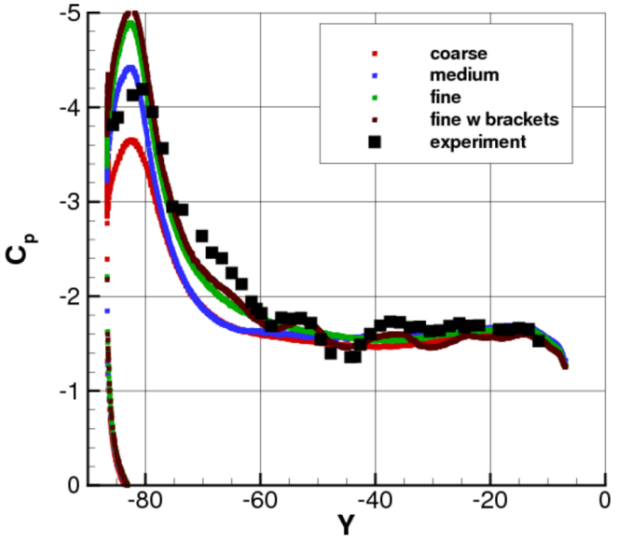
Entry 003.01



Entry 007



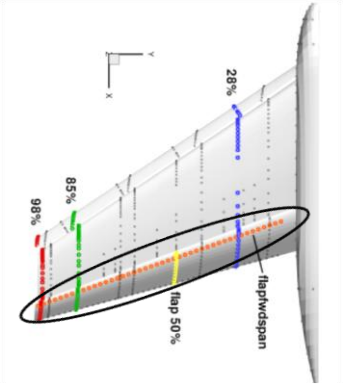
Entry 009



Dips in experiment predicted

Note entry 009 over-predicted suction at tip

-<u>All</u> other entries under-predicted it



STATISTICAL ANALYSIS

What to watch for

- Statistical analysis can be helpful to identify potential outliers
- Variation between CFD results decreased as grid was refined
  - Even smaller variation if include only results from one turbulence model
- Quantitative assessment of trends in forces and moment (between configurations 1 and 8)

Statistical analysis

- Method of Morrison adopted
  - AIAA 2010-4673 (DPW analysis)
- Scatter limits

$$\hat{\mu} \pm K\hat{\sigma}$$

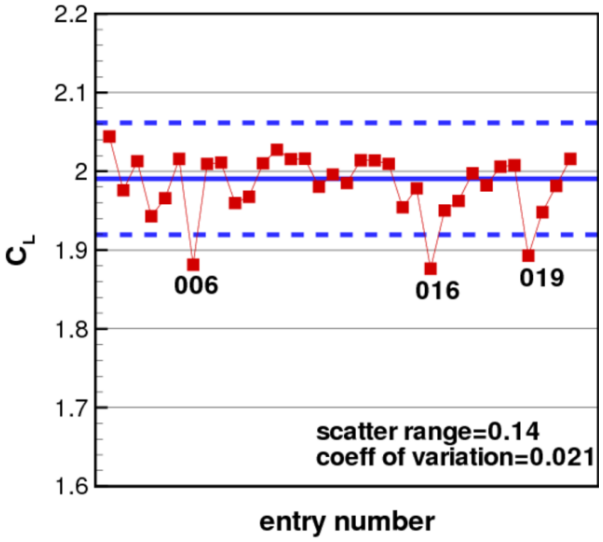
  - $\hat{\mu}$ is the median of sorted data (median is robust in presence of outliers)
  - $\hat{\sigma}$ is standard deviation
  - K is confidence interval coverage factor
    - Taken to be $\sqrt{3}$ (chosen based on assumed uniform distribution)
    - Note that Hemsch & Morrison (AIAA 2004-556) used more conservative value of 3
  - "Outliers" are submissions that reside outside of the scatter limits
    - Indication of potentially significant CFD difference
    - May need to be investigated, to understand the cause
- Coefficient of variation

$$C_v = \hat{\sigma} / \hat{\mu}$$

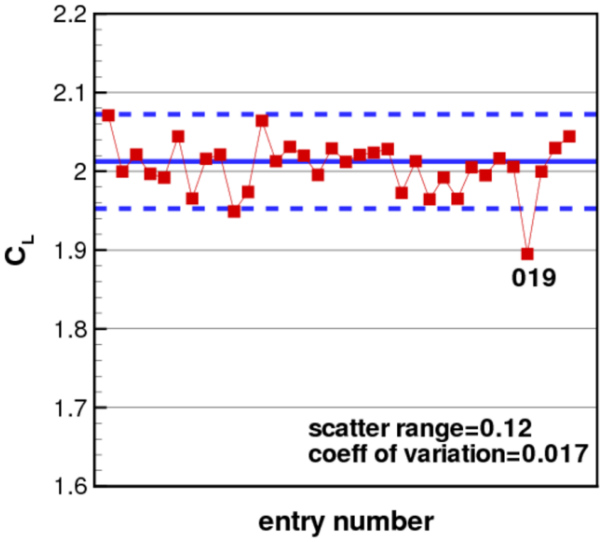
All entries, alpha=13°

Lift Coefficient

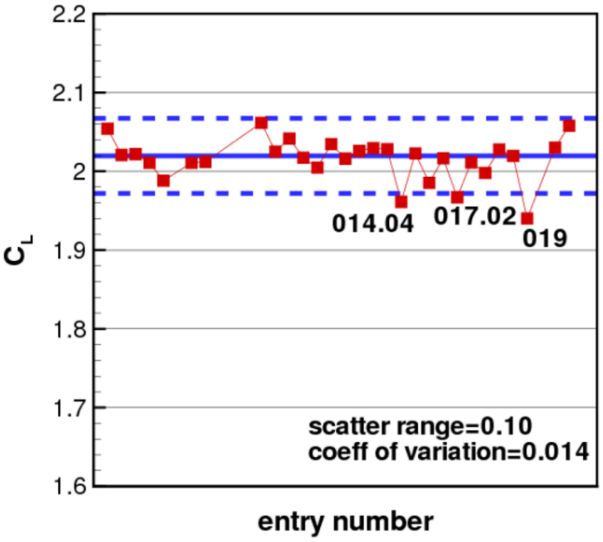
Coarse grid



Medium grid



Fine grid

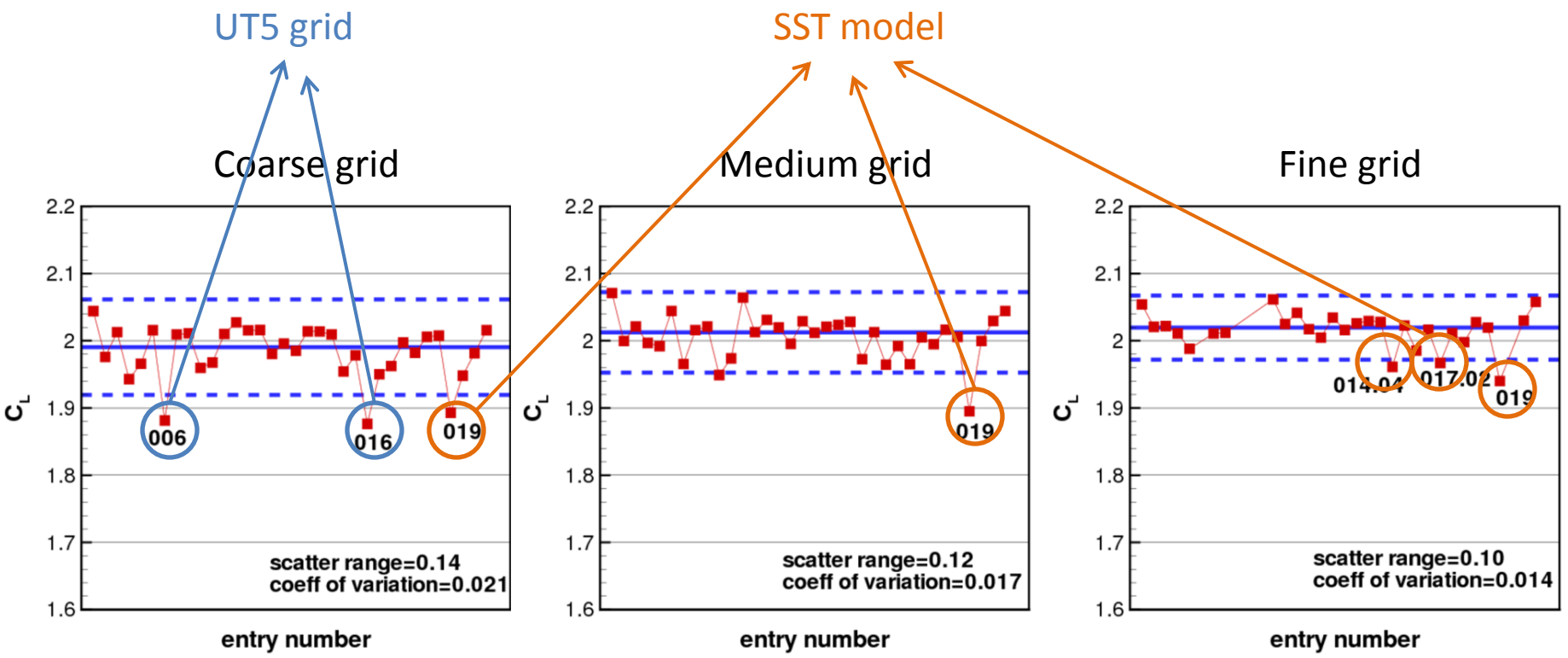


-Range of scatter limits and coefficient of variation decreased as grid was refined

-Similar story for C_D and C_M

All entries, alpha=13°

Lift Coefficient



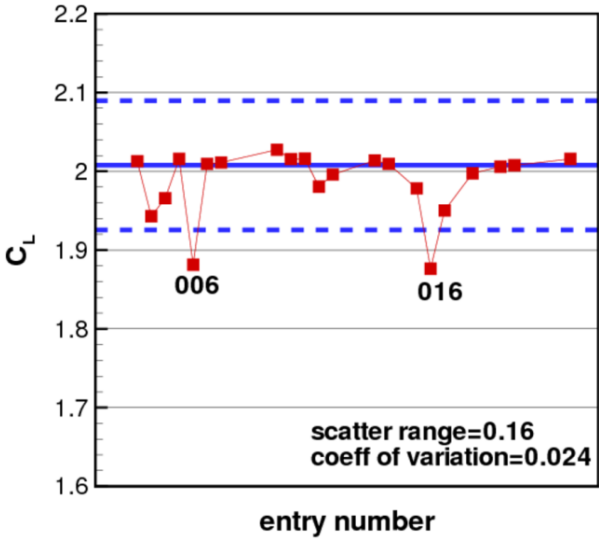
-Range of scatter limits and coefficient of variation decreased as grid was refined

-Similar story for C_D and C_M

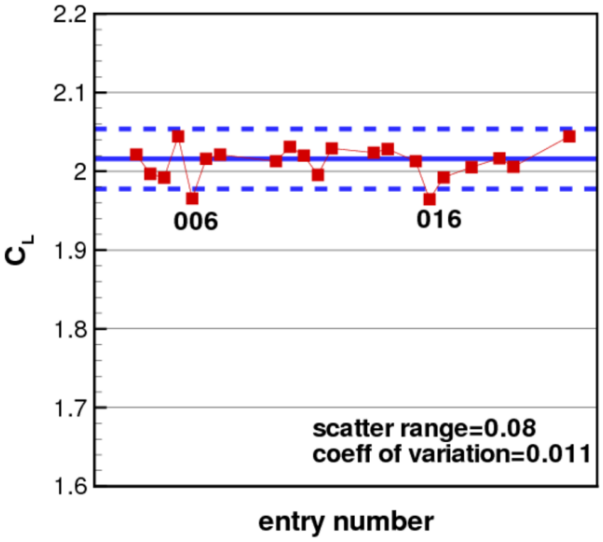
SA entries, alpha=13°

Lift Coefficient

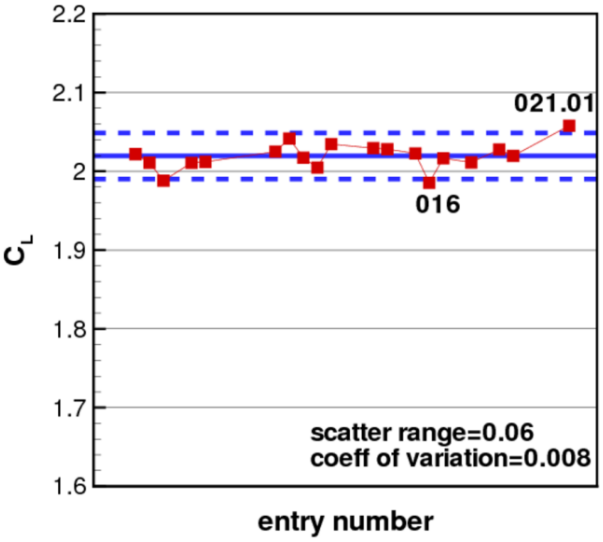
Coarse grid



Medium grid



Fine grid



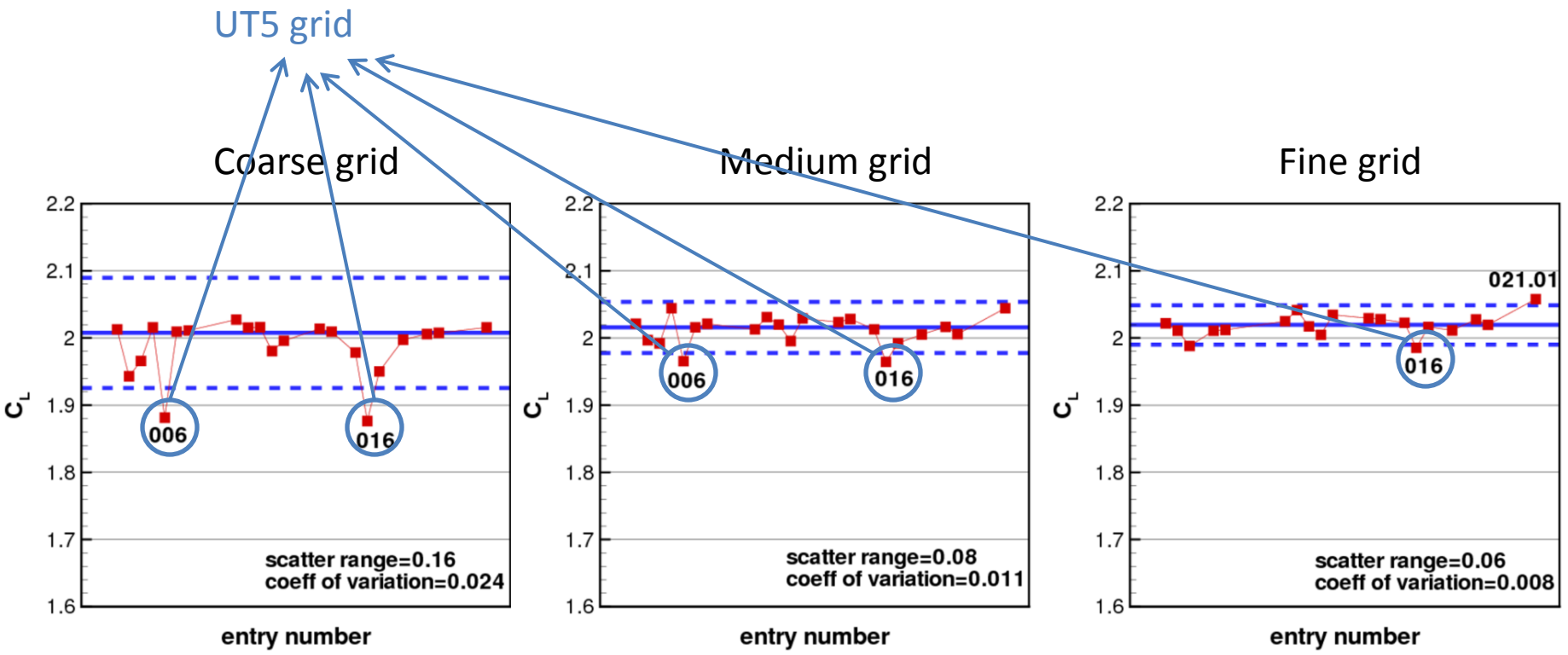
-Range of scatter limits and coefficient of variation decreased as grid was refined

-Smaller variation (on M & F) for SA alone

-Similar story for C_D and C_M

SA entries, alpha=13°

Lift Coefficient

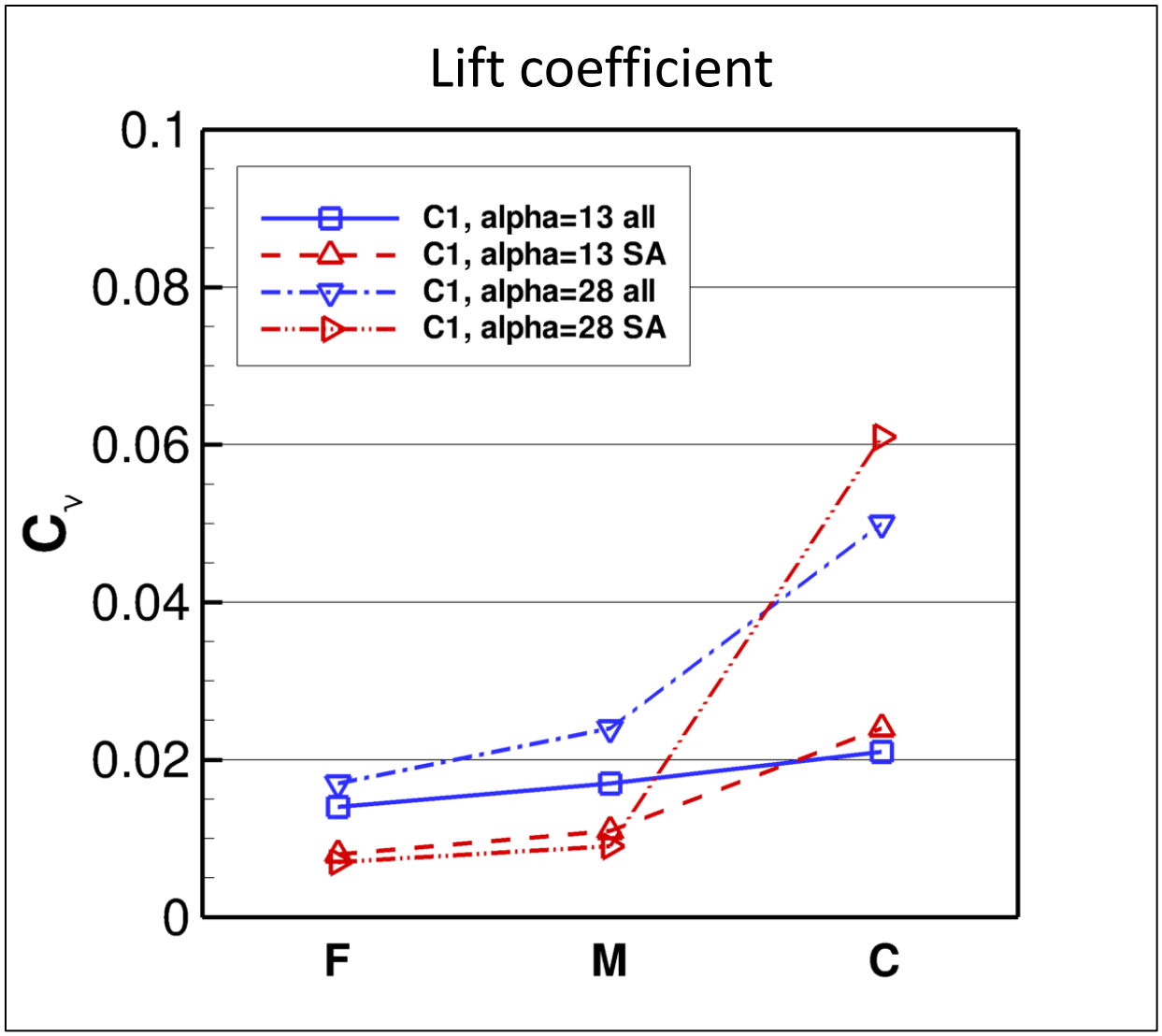


-Range of scatter limits and coefficient of variation decreased as grid was refined

-Smaller variation (on M & F) for SA alone

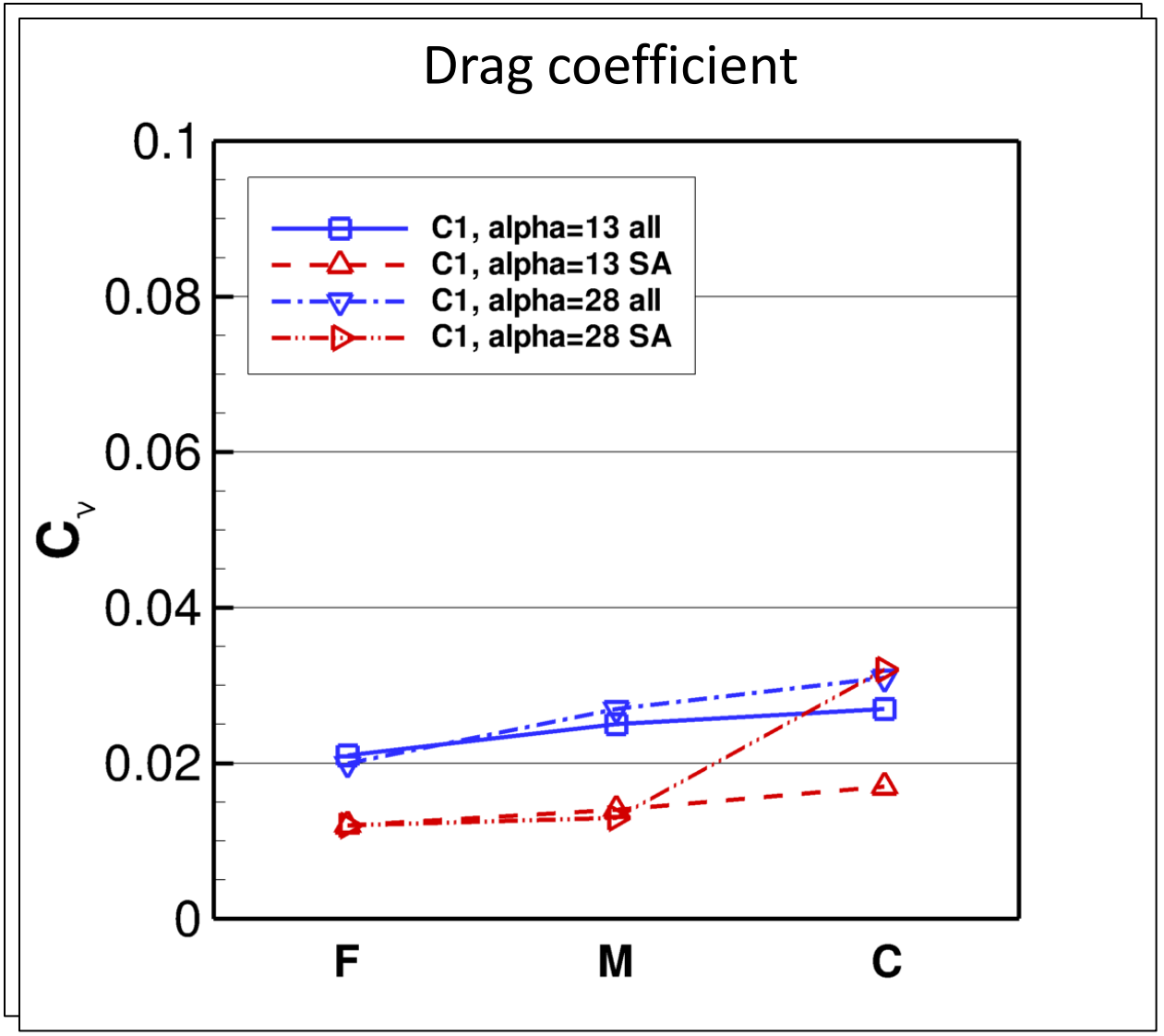
-Similar story for C_D and C_M

Effect of grid refinement on coefficient of variation



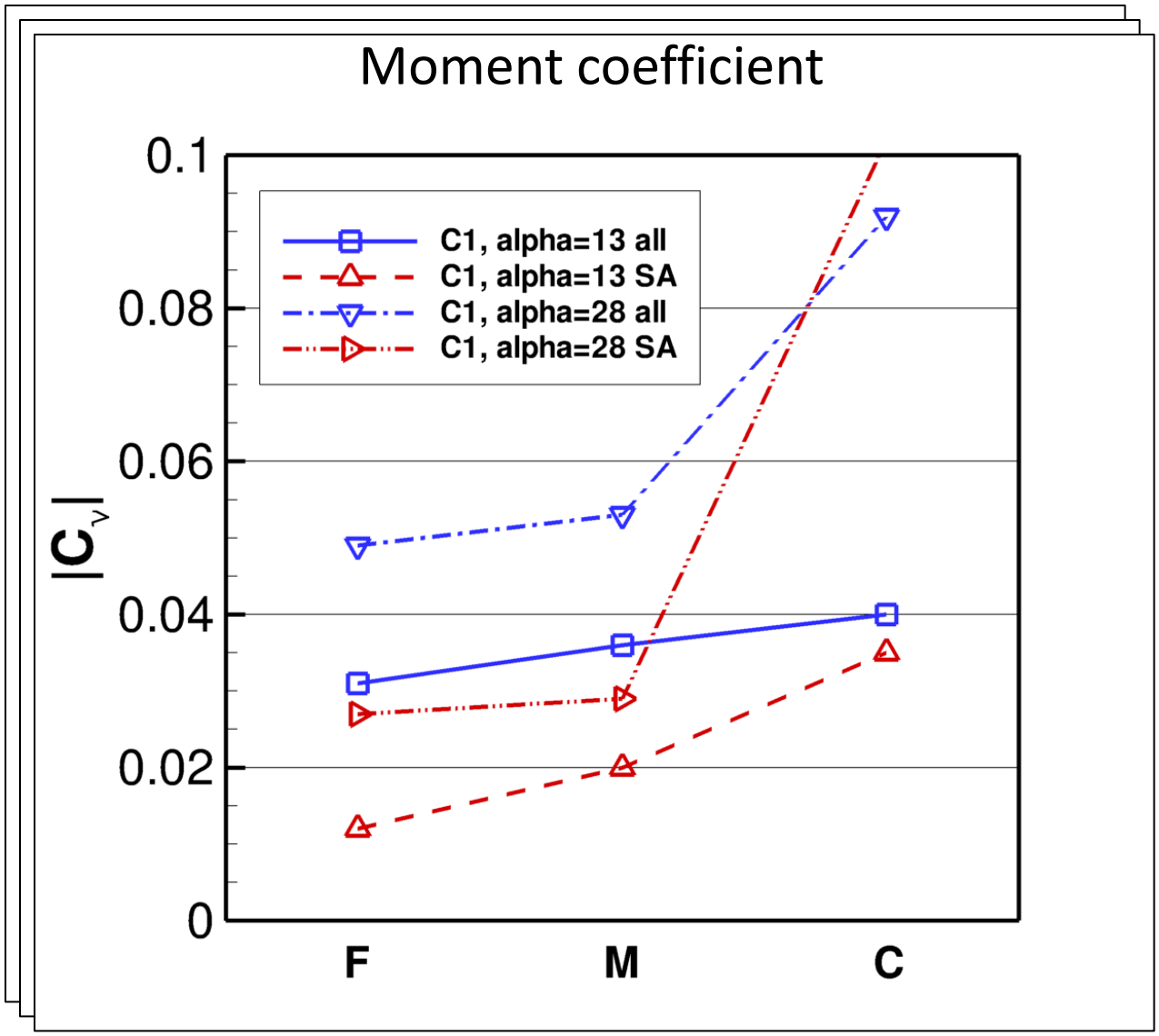
finer grid ←

Effect of grid refinement on coefficient of variation



finer grid ←

Effect of grid refinement on coefficient of variation

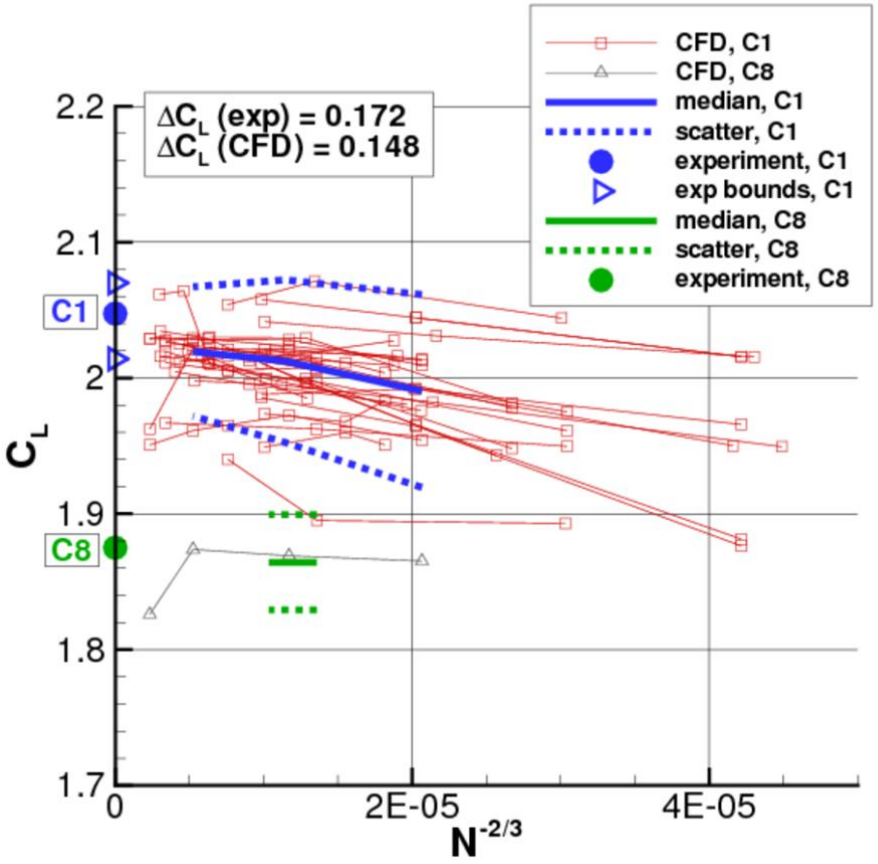


Grid convergence, alpha=13°

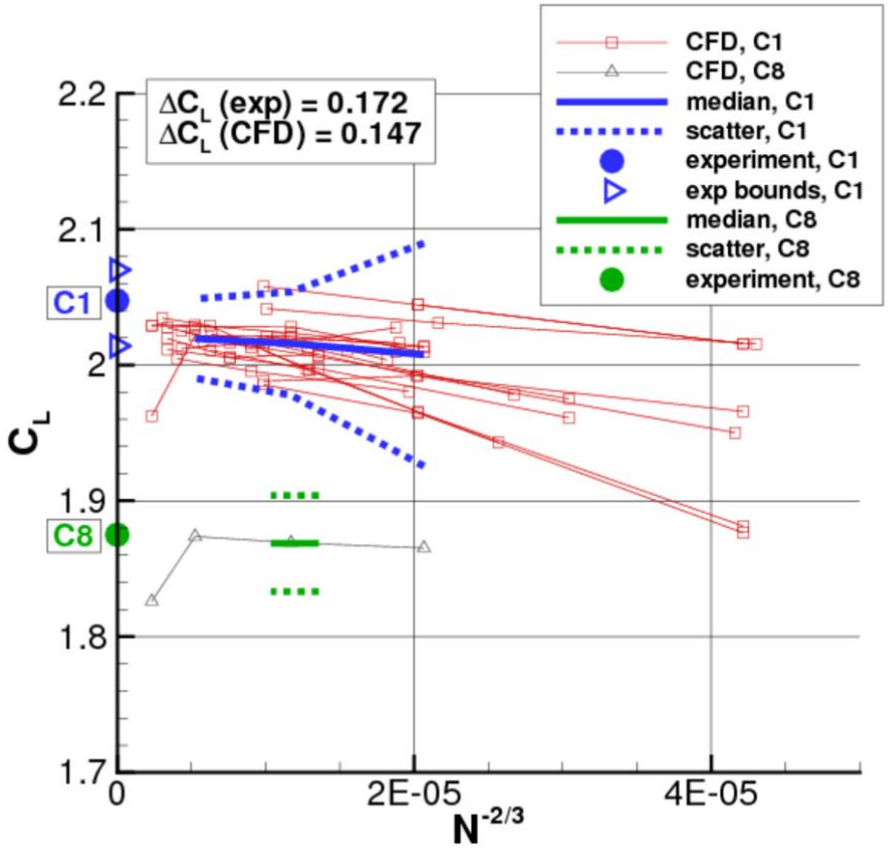
Showing differences between configurations 1 and 8

Lift coefficient

All entries



SA only

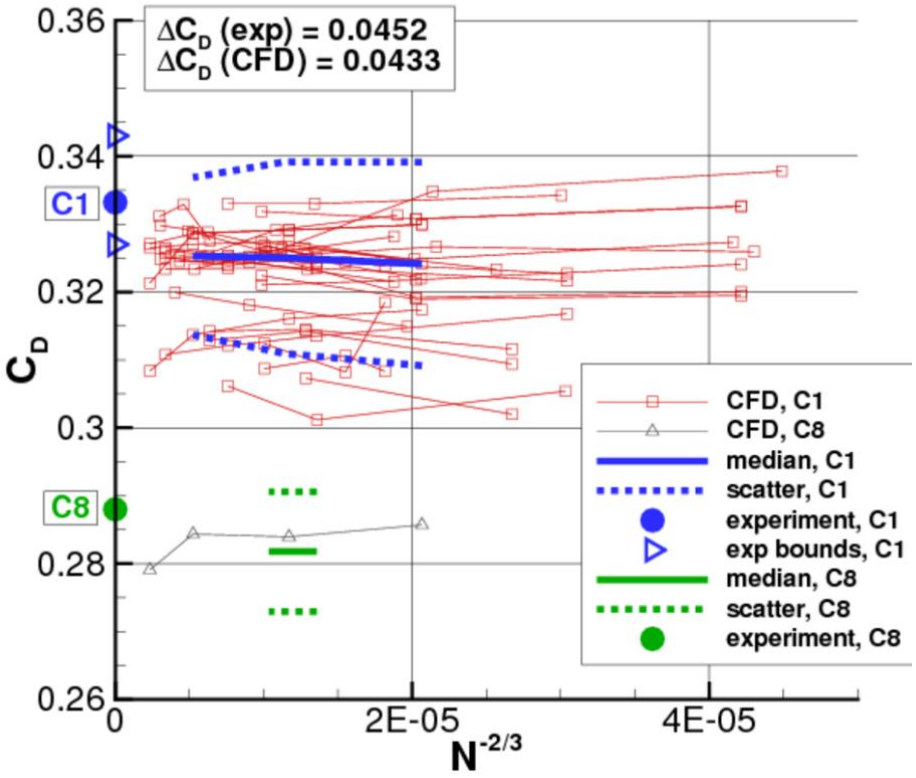


Grid convergence, alpha=13°

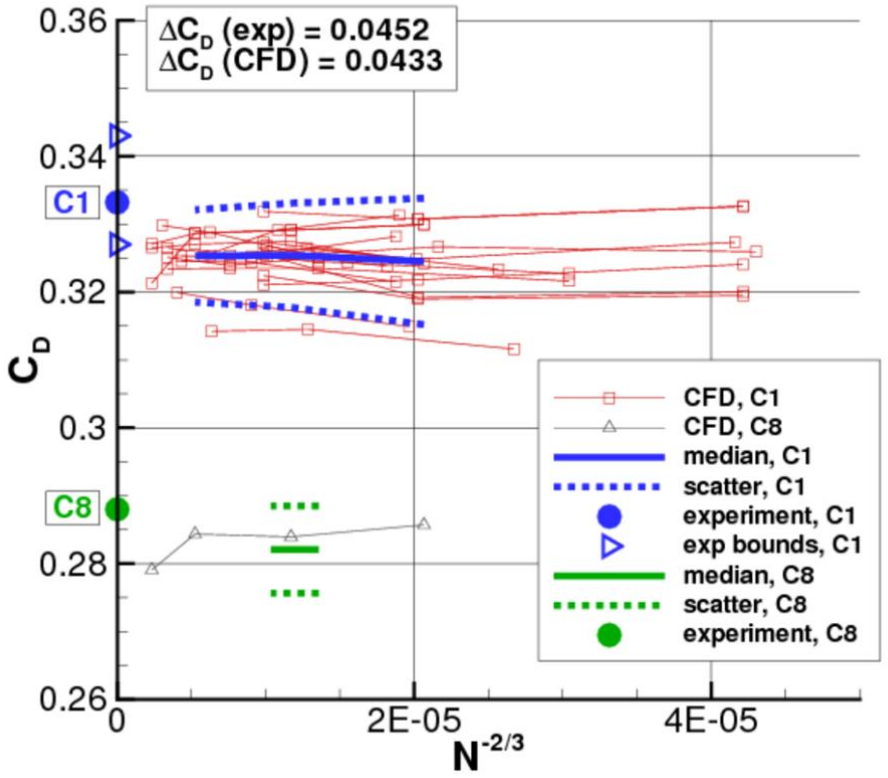
Showing differences between configurations 1 and 8

Drag coefficient

All entries



SA only

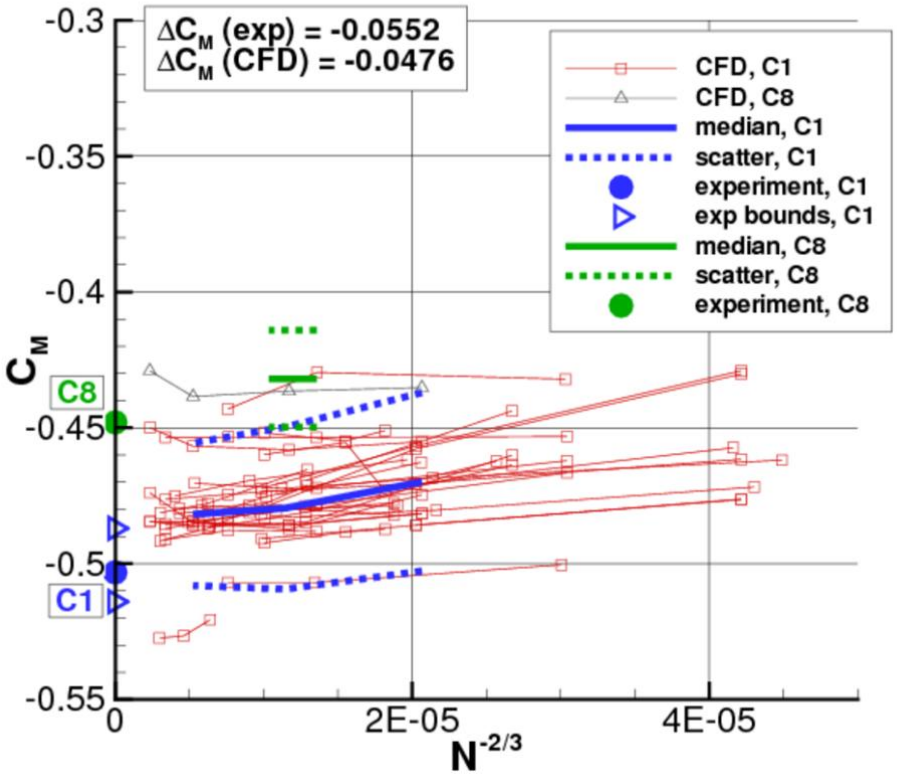


Grid convergence, alpha=13°

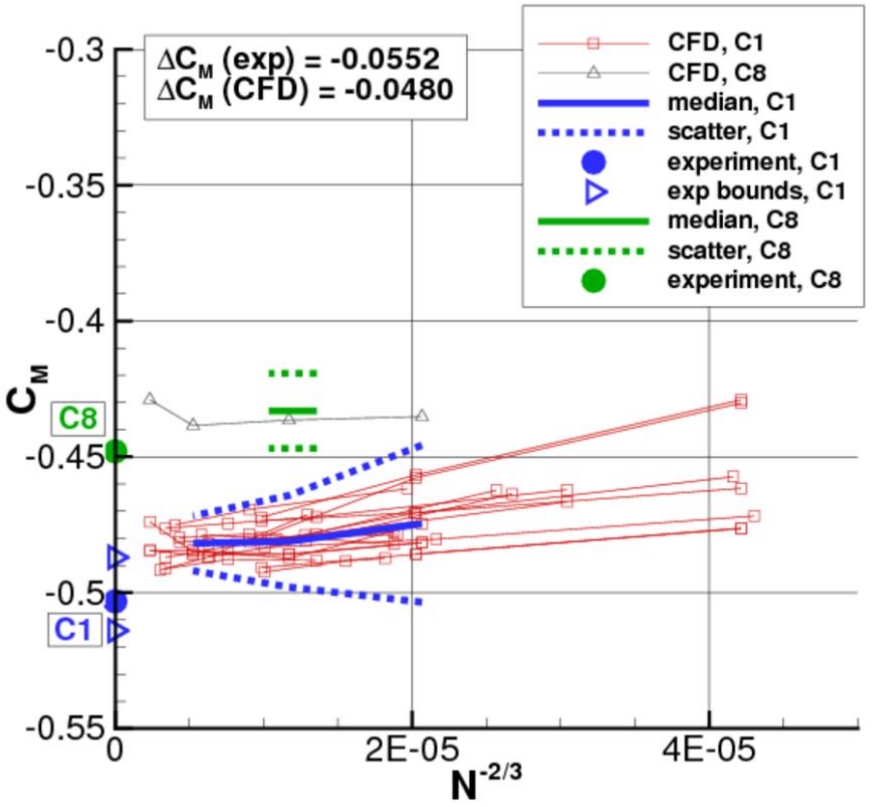
Showing differences between configurations 1 and 8

Moment coefficient

All entries



SA only

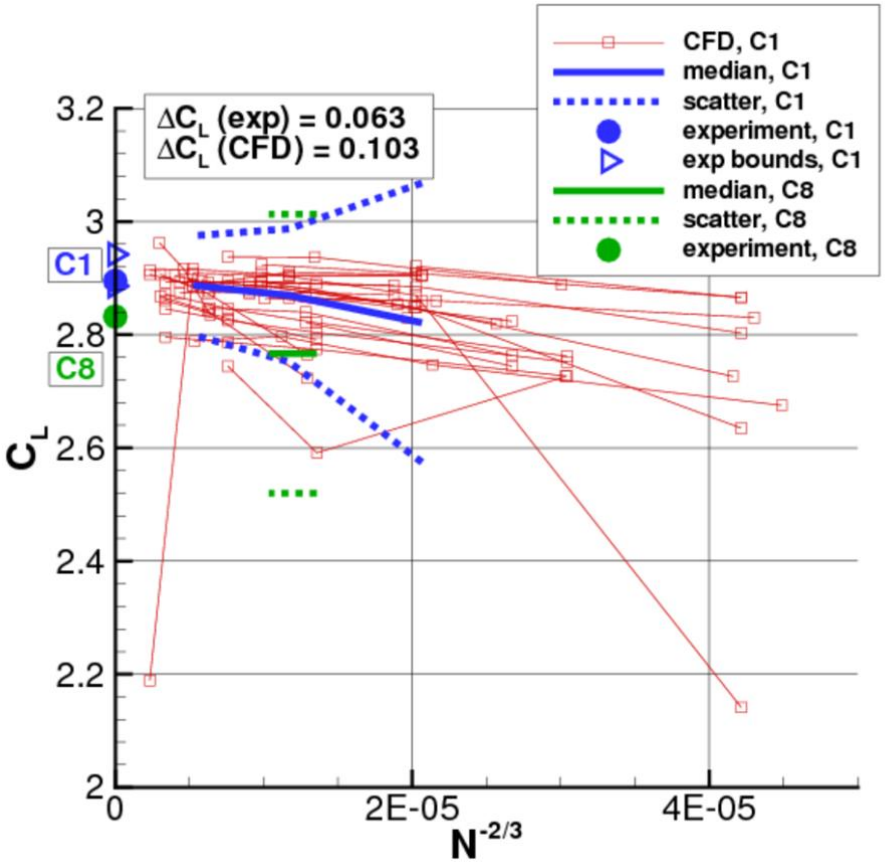


Grid convergence, alpha=28°

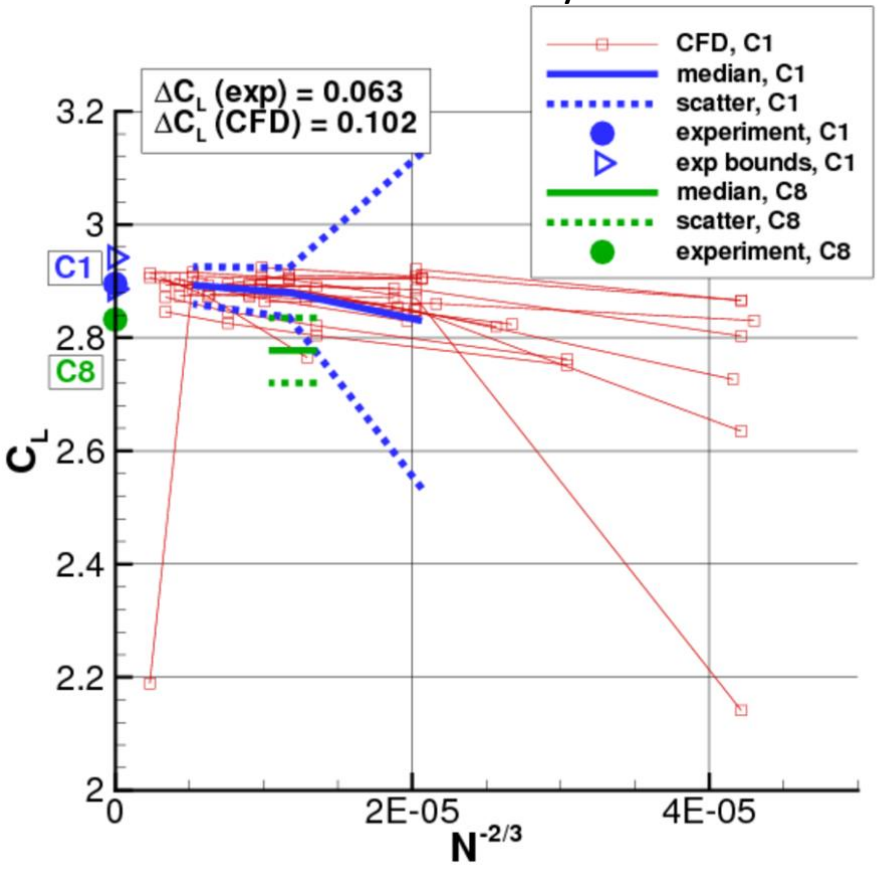
Showing differences between configurations 1 and 8

Lift coefficient

All entries



SA only

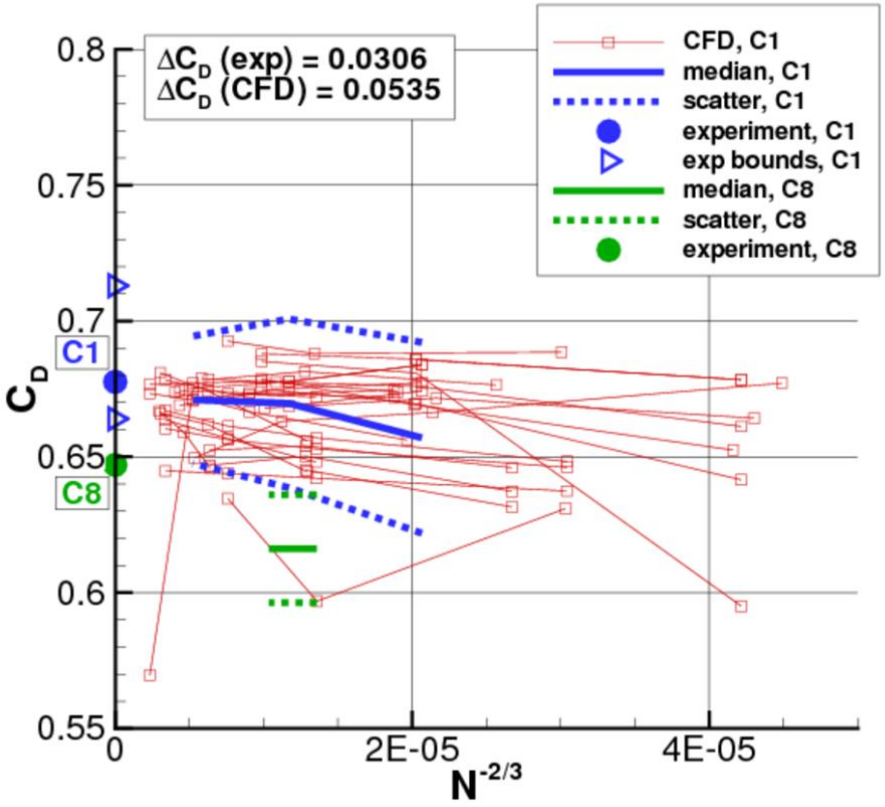


Grid convergence, alpha=28°

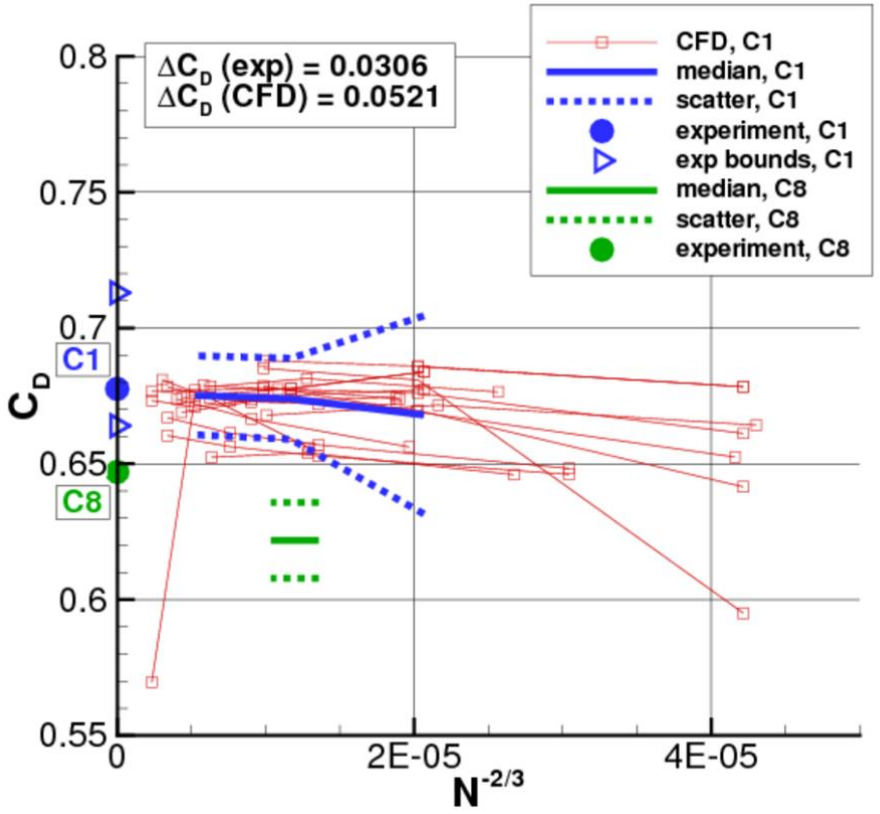
Showing differences between configurations 1 and 8

Drag coefficient

All entries



SA only

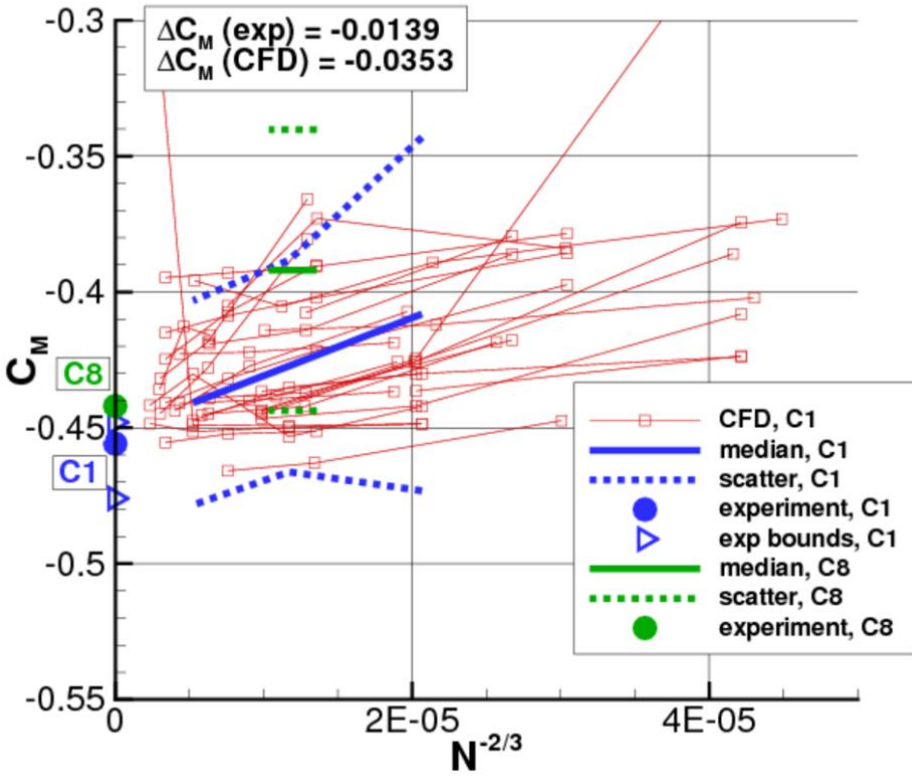


Grid convergence, alpha=28°

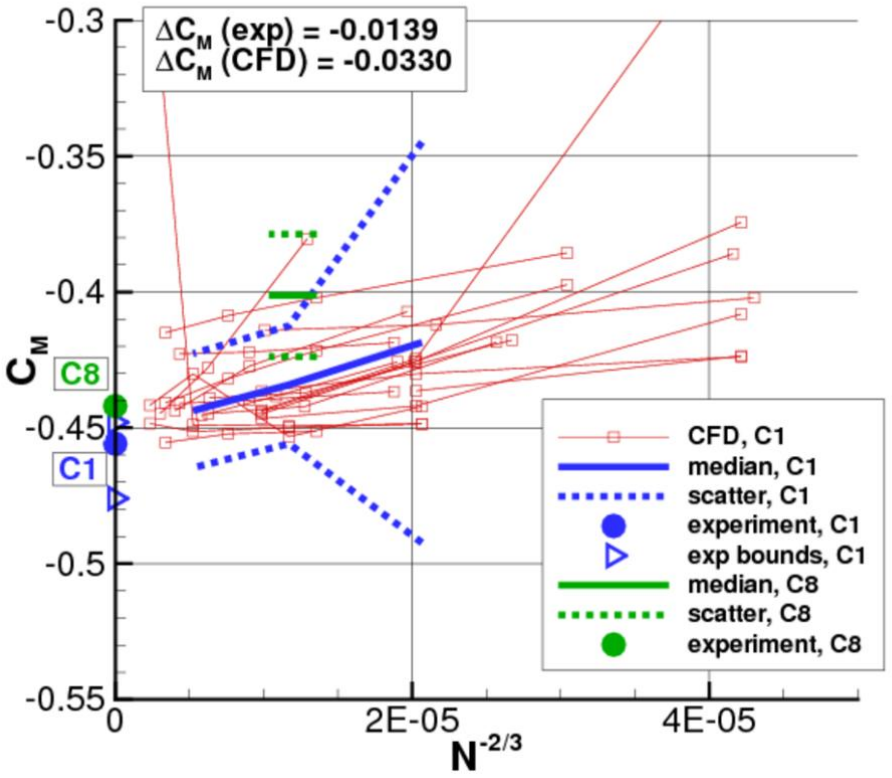
Showing differences between configurations 1 and 8

Moment coefficient

All entries



SA only



Conclusions

- This summary has assessed current CFD prediction capability for the NASA Trapezoidal wing
- Identified influence & potential importance of including support brackets in CFD analysis (they affect forces & moments)
- Configuration differences (Config 1 vs. Config 8)
  - CFD deltas too low by 4-15% at alpha=13^{o}
  - CFD deltas too high by 62-154% at alpha=28^{o}
  - Lack of grid study for Config 8 limits ability to draw firm conclusions
- Identified areas needing additional attention
  - Wing tip region (CFD generally poor)
  - Outboard flap trailing edge region (higher variability among CFD)
  - Influence of transition
  - Effect of initial conditions on CFD solutions
- Planning is underway for HiLiftPW-2

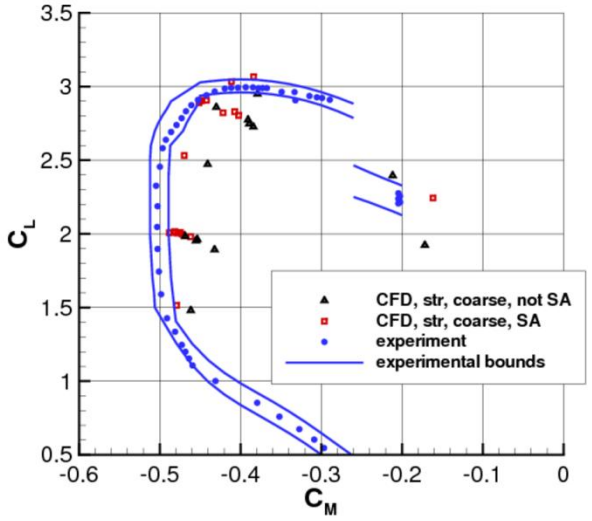
BACKUP SLIDES

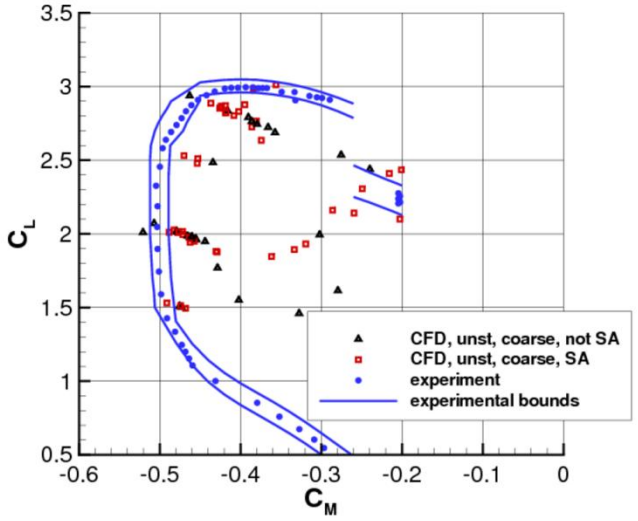
Moment polars for configuration 1

Structured

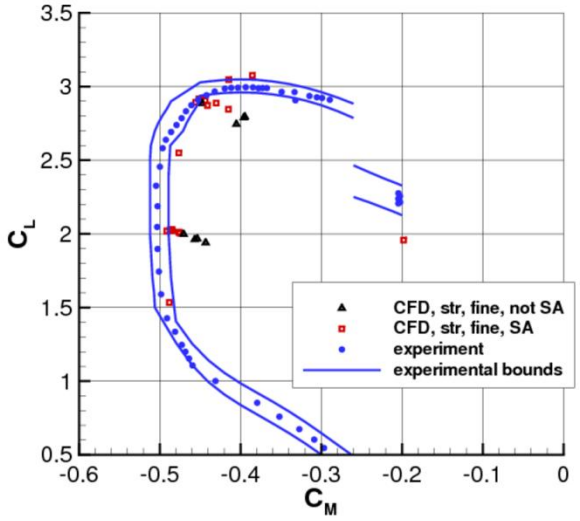
Unstructured

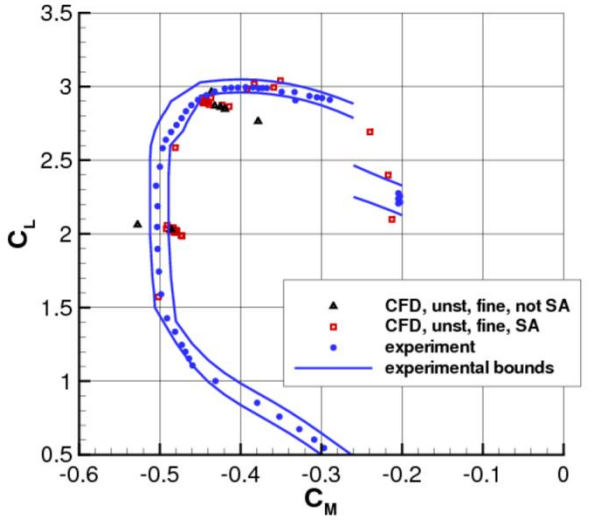
Coarse Grid





Fine Grid





Summary

- Overall CFD results
  - Tended to under-predict lift, drag, and magnitude of moment compared to experiment
  - Nonetheless, many participants predicted $C_{L,max}$ reasonably well
  - More spread among CFD solutions at high angles of attack
  - Wing tip region difficult for CFD to predict accurately
    - All entries but one under-predicted suction levels there
    - Thin-layer type approximation yielded particularly poor results near wing tip
  - More C_p variation among CFD results near T.E. of flap at outboard stations
  - Several participants reported initial condition dependency, particularly at high alphas

Summary, cont'd

- Turbulence models
  - Most people used SA
  - SST model showed greater tendency to separate than SA
  - On the whole, SA tended to yield higher lift than other models, in better agreement with experiment
  - Two notable exceptions to this were non-SA models that included transition

Summary, cont'd

- Grid refinement trends
  - Generally in the correct direction (toward experiment)
  - But faithful modeling may need to include:
    - Support brackets
    - Transition
  - Unstructured grids exhibited greater variability than structured grids on Coarse level, but Fine level results were similar
  - Tetrahedral grid exhibited greater grid sensitivity than a mixed element version (tets merged to prisms in BL) of the same grid
  - Variation between CFD results decreased as grid was refined
  - Even smaller variation if include only results from one turbulence model

Summary, cont'd

- Other trends
  - Including brackets (medium grid)
    - Decreased lift
      - Alpha=13°: Delta C_L=0.015
      - Alpha=28°: Delta C_L=0.074
    - Improved C_p comparisons at some locations
    - Impact of brackets near $C_{L,max}$ not established in this study
  - Configuration differences (Config 1 vs. Config 8)
    - CFD Δ too low by 4-15% at alpha=13°
    - CFD Δ too high by 62-154% at alpha=28°
    - Lack of grid study for Config 8 limits ability to draw firm conclusions